

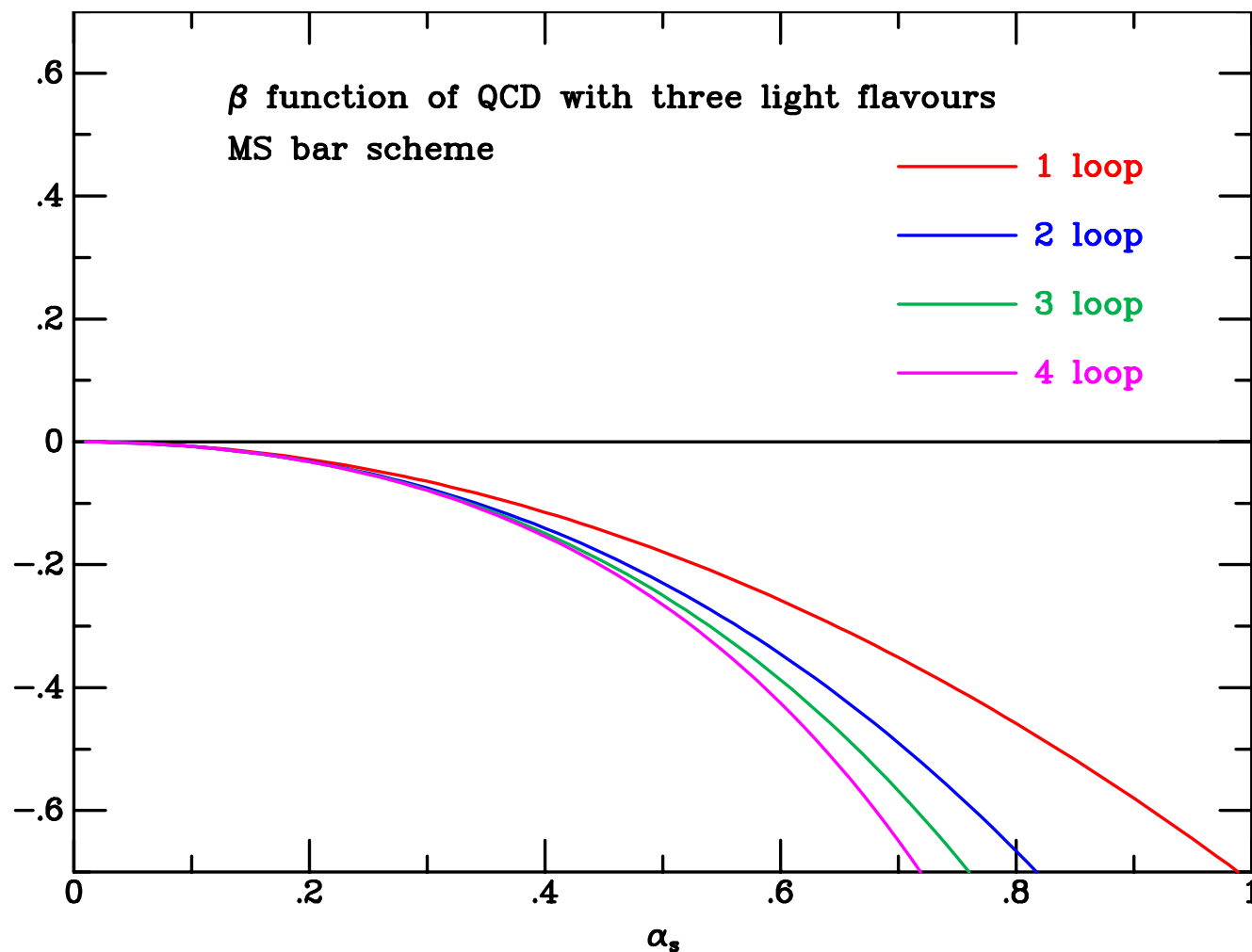
# QCD in the 21st century

Keith Ellis  
Fermilab

# Asymptotic freedom

Back in 1973....

$$\mu^2 \frac{\partial \alpha_s}{\partial \mu^2} = \beta(\alpha_s)$$



national accelerator laboratory

NAL-PUB-73/49-THY

July, 1973

ASYMPTOTICALLY FREE GAUGE THEORIES - I\*

David J. Gross<sup>†</sup>  
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Joseph Henry Laboratories  
Princeton University  
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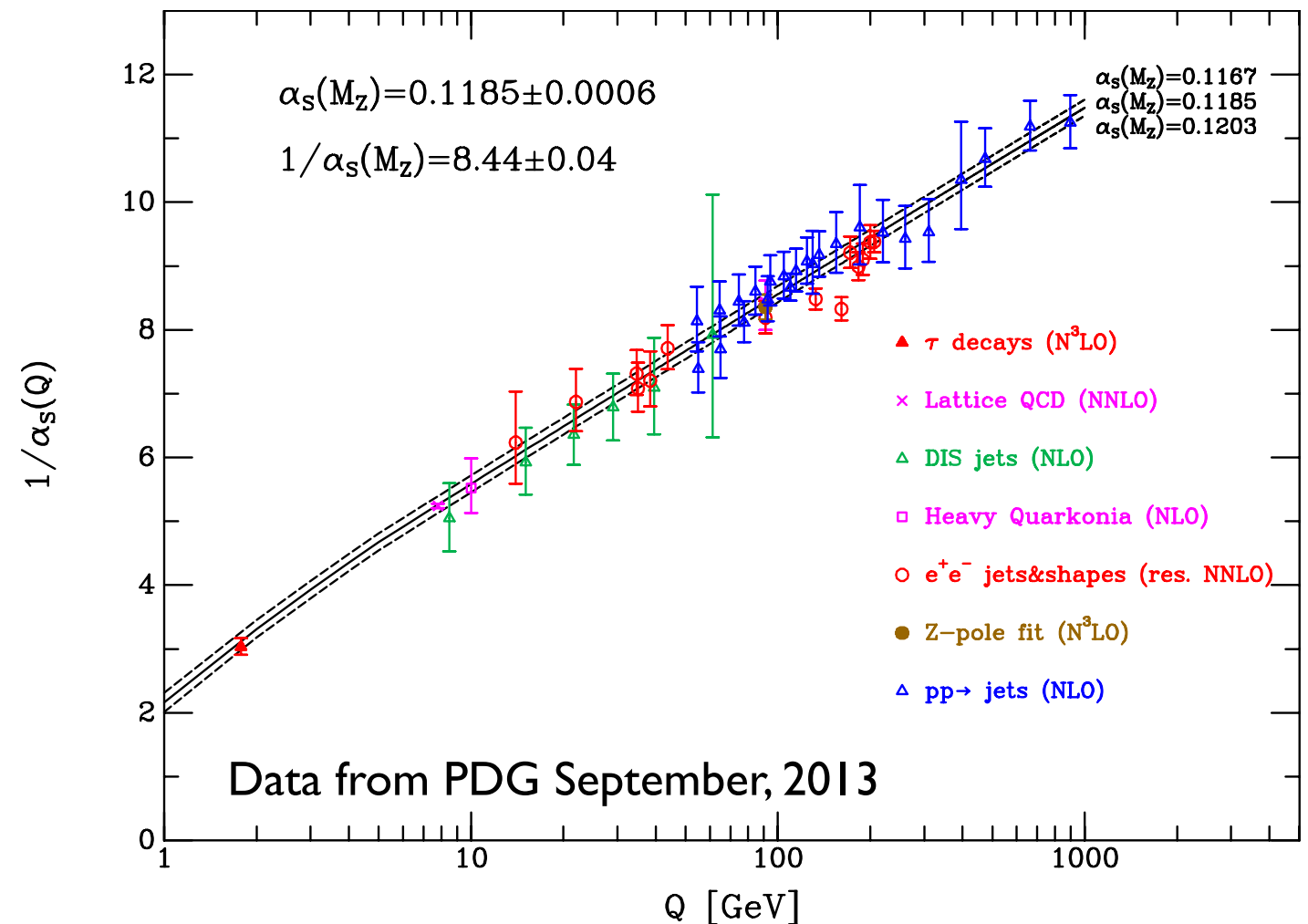
\*Research supported in part by the United States  
Air Force Office of Scientific Research under  
Contract F-44620-71-6-0180

<sup>†</sup>Alfred P. Sloan Foundation Research Fellow

Theory  
summer  
program

# Running coupling, $\alpha_s$

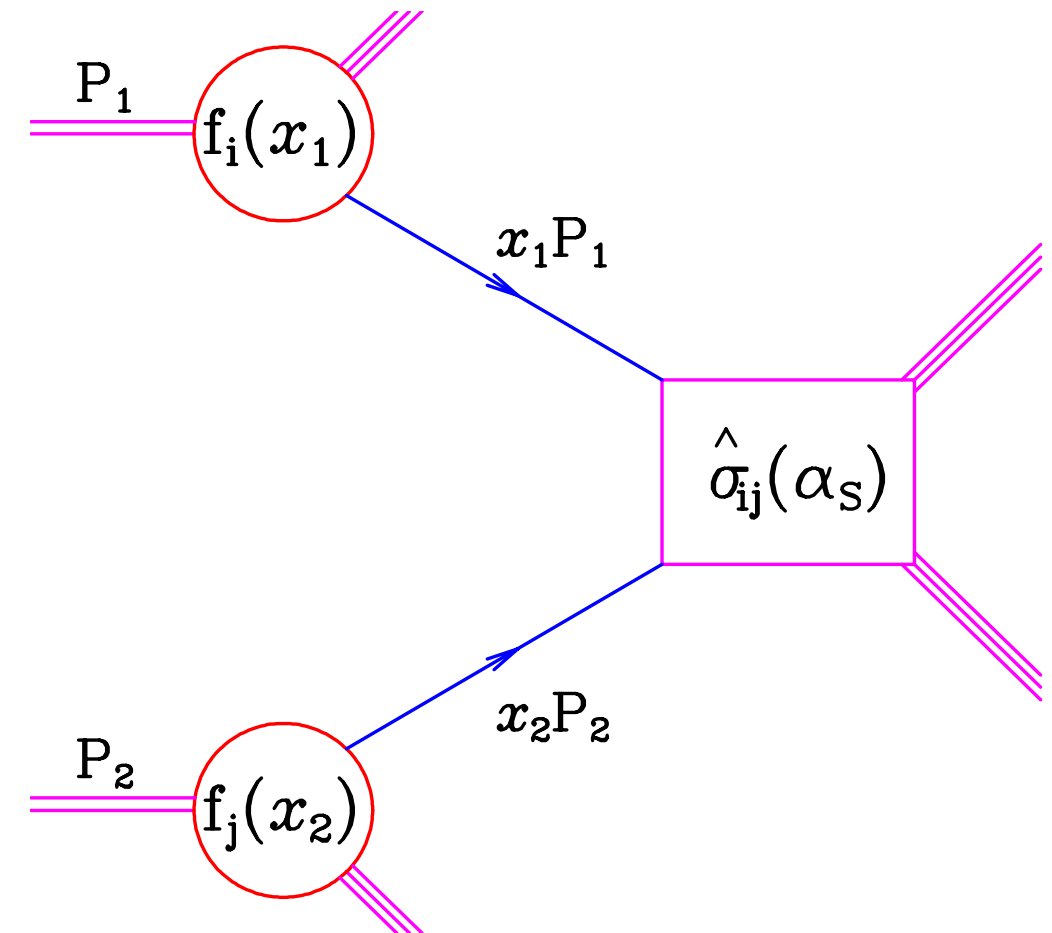
- Incontrovertible fact that  $\alpha_s$  is smallish at energies accessible with current machines.
- $1/\alpha_s$  as grows as  $\log(Q)$ .
- $1/\alpha_s(M_Z)=8.44$
- c.f QED:  $1/\alpha(M_Z)=128....$
- Radiative corrections  $\sim 15$  times more important in QCD than QED.



Also some other outliers mainly from  $e^+e^-$  data  
 Abbate, 1006.3080,  $\alpha_s(M_Z)=0.1135\pm0.0010$   
 Hoang, 1501.04753,  $\alpha_s(M_Z)=0.1123\pm0.0002$

# QCD improved parton model

- Hard cross section is represented as a convolution of a short-distance cross section and non-perturbative parton distribution functions.
- Physical cross section is formally independent of  $\mu_R$  and  $\mu_F$  through the order calculated.
- Here we shall be concerned with the short distance cross section.



$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F) f_j(x_2, \mu_F) \hat{\sigma}_{ij}(p_1, p_2, \alpha_s(\mu_R^2), Q^2, \mu_R, \mu_F).$$

Physical cross section

Parton distributions

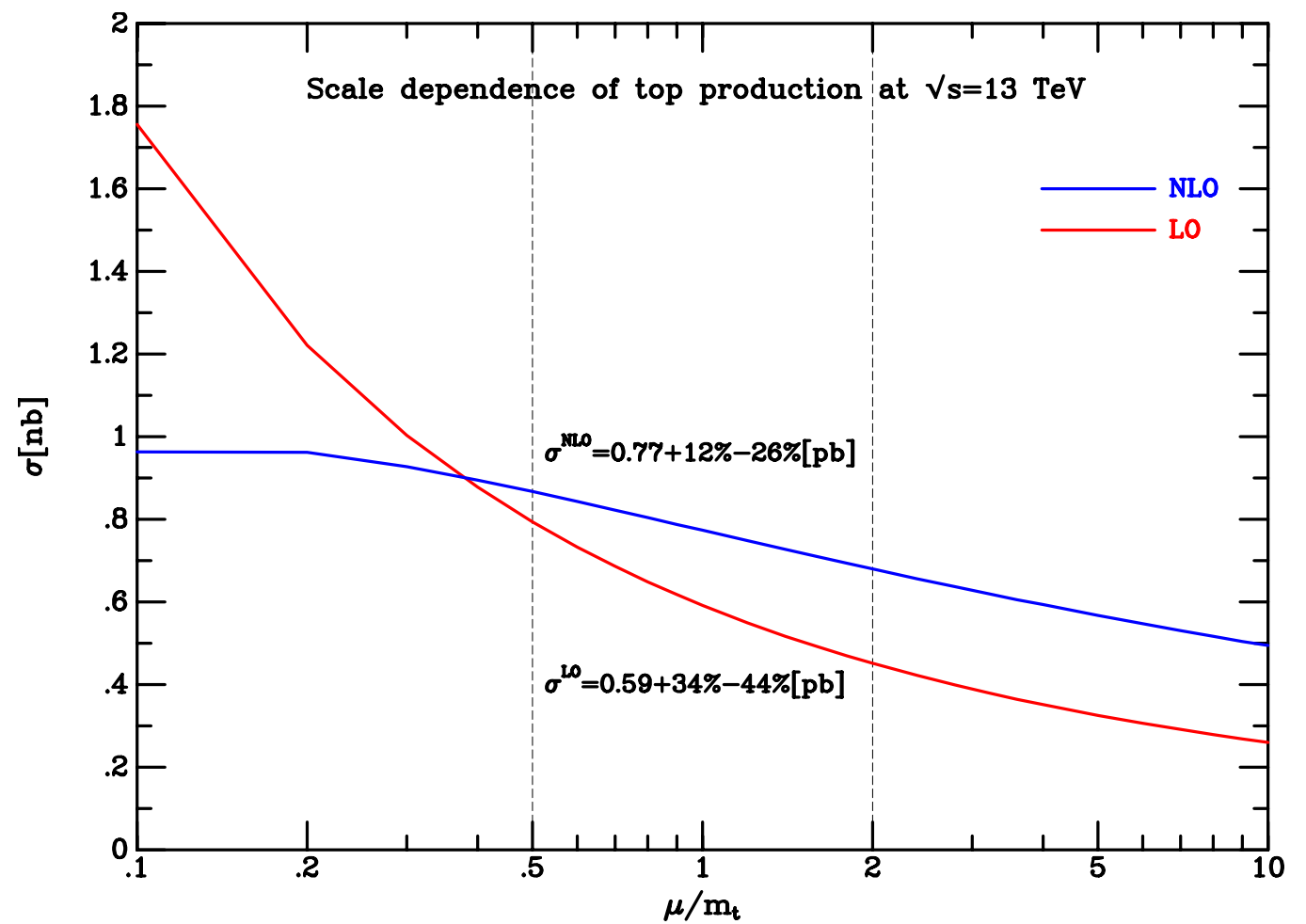
Factorization scale

Renormalization scale



# Higher order perturbative QCD: why bother?

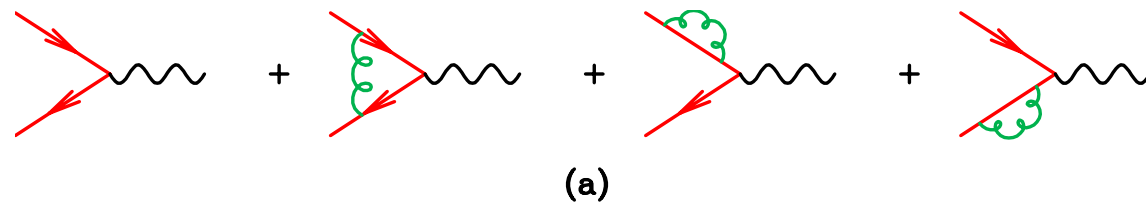
- Take top pair production at 13 TeV.
- Higher order terms are not the 12% suggested by the size of  $\alpha_s$ , because of the special nature of renormalization group improved perturbation theory.
- Given that e.g. the luminosity measurement at the LHC is in the range 2-5% we need to do better than 12% anyway.



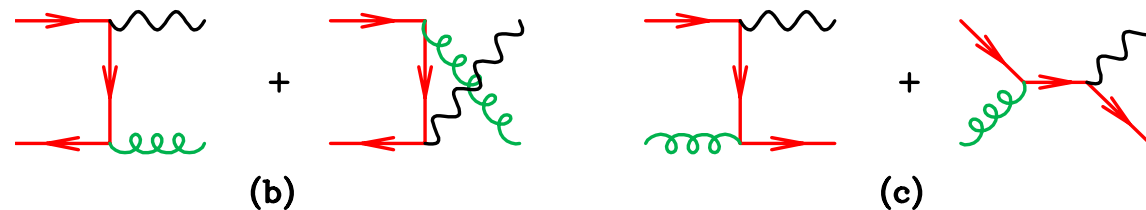
$$\mu_R = \mu_F = \mu$$

# Ingredients in a NLO calculation

- Consider vector boson production



Virtual diagrams



Real diagrams

- Real and virtual diagrams live in different phase spaces
- For the virtual diagrams (lower multiplicity) the infrared poles are explicit, whereas as for real diagrams (higher multiplicity), they appear after integration.
- The necessity to integrate to cancel poles, is at variance with the desire for a differential distribution.

# Perturbative QCD 2000-2010

- Prehistory
- MCFM (inclusion of many processes at NLO).
- NLO is the first approximation which gives an idea of a suitable choice for  $\mu$ .
- The rise of automatic procedures.
- Semi-numerical methods for Feynman diagrams.
- Next-to-leading order (NLO) revolution

# $\alpha_s$ corrections to the Drell-Yan process

- the birth of precision hadronic collider physics
- resolved ambiguities associated with the colour degree of freedom.
- The first 'K' factor calculation
- No agreement with data without NLO contributions.
- State of the art until NNLO was calculated NPB382 (1992) !!

## LARGE PERTURBATIVE CORRECTIONS TO THE DRELL-YAN PROCESS IN QCD \*

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Rome 00185, Italy*

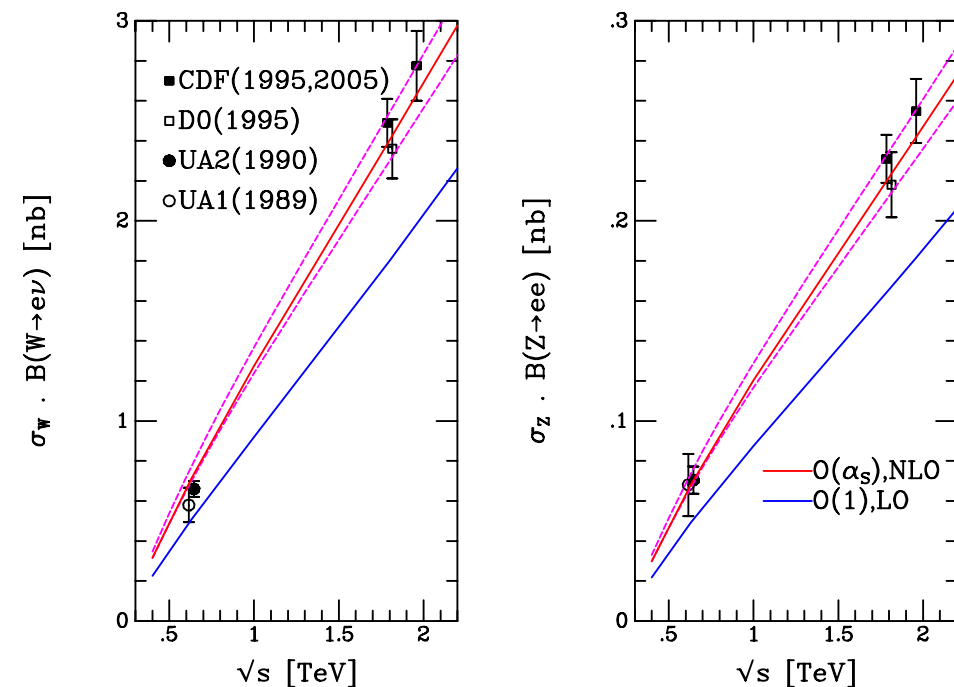
R.K. ELLIS

*Center for Theoretical Physics,  
Laboratory for Nuclear Science and Department of Physics,  
Massachusetts Institute of Technology,  
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G. MARTINELLI

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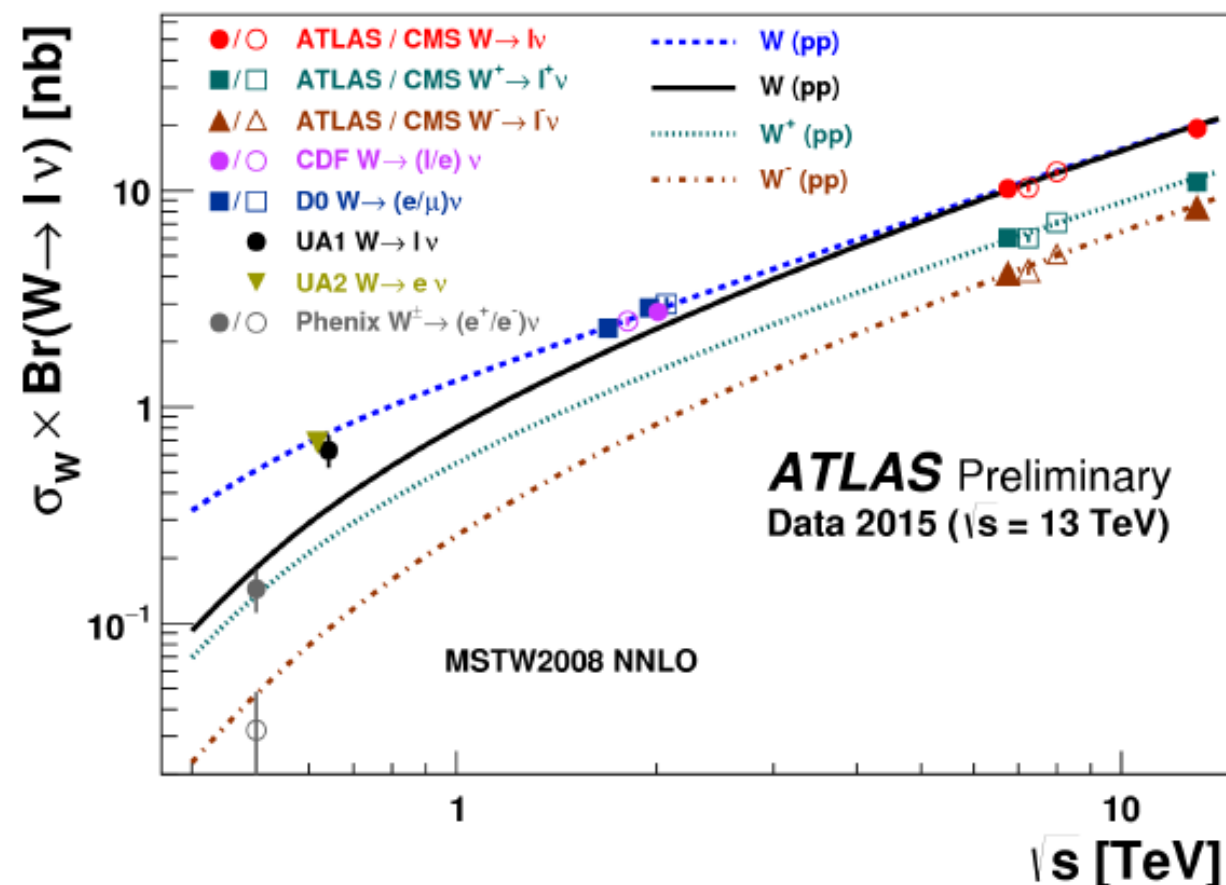
Guido Altarelli, Guido Martinelli



Keith Ellis, W&C, 8/21/2015

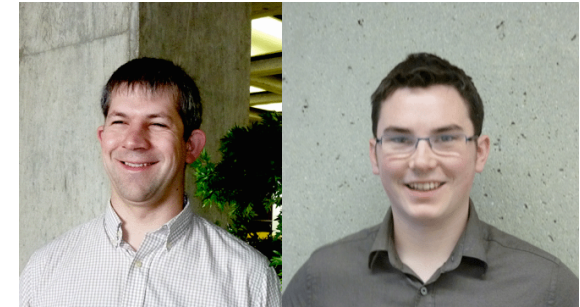
## Comparison with data from low to high energy

- Basic DY mechanism is the same for  $W, Z$  production.
- Beautifully confirmed by  $W^\pm$  production from  $\sqrt{s}=0.54\text{-}13\text{TeV}$ .



But we need to go beyond total cross sections.....

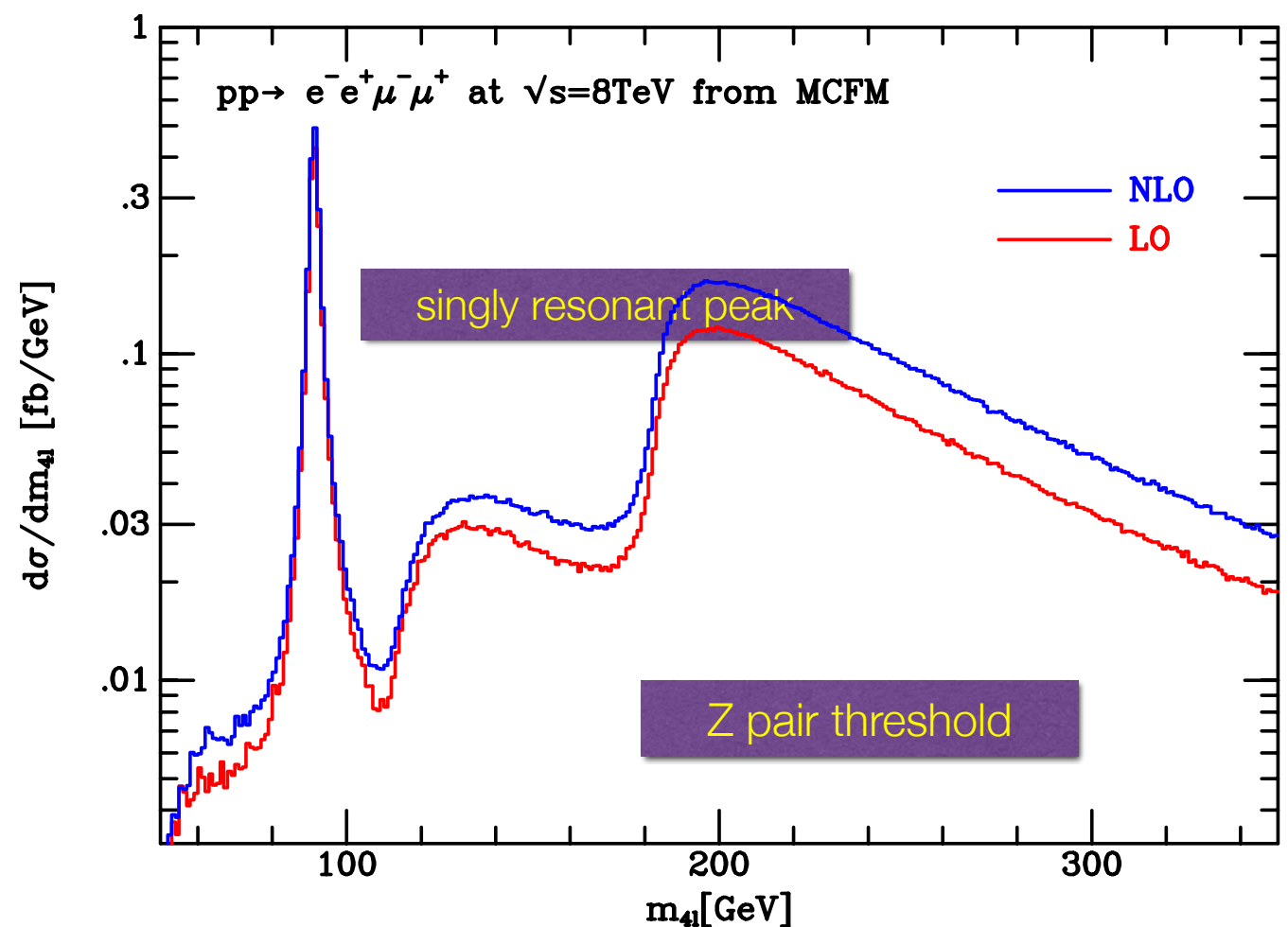
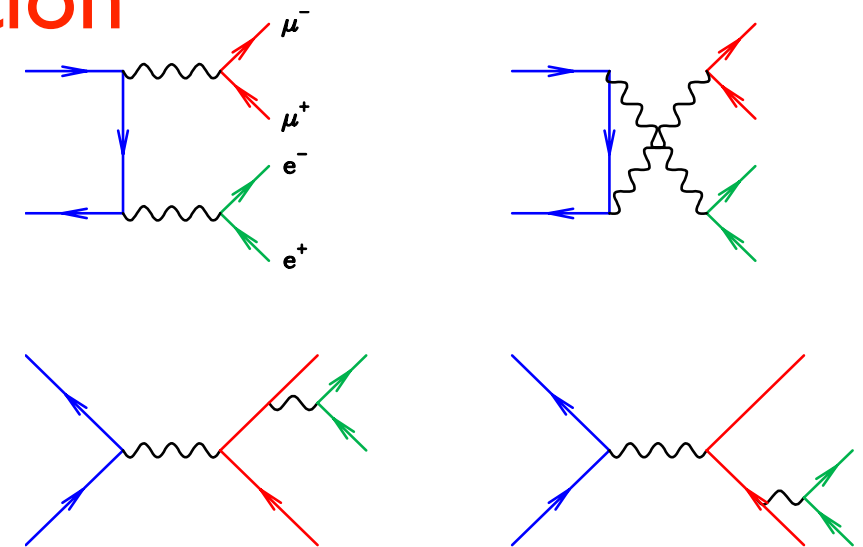
# MC<sup>2</sup>FM (Monte Carlo for FeMtobarn processes)



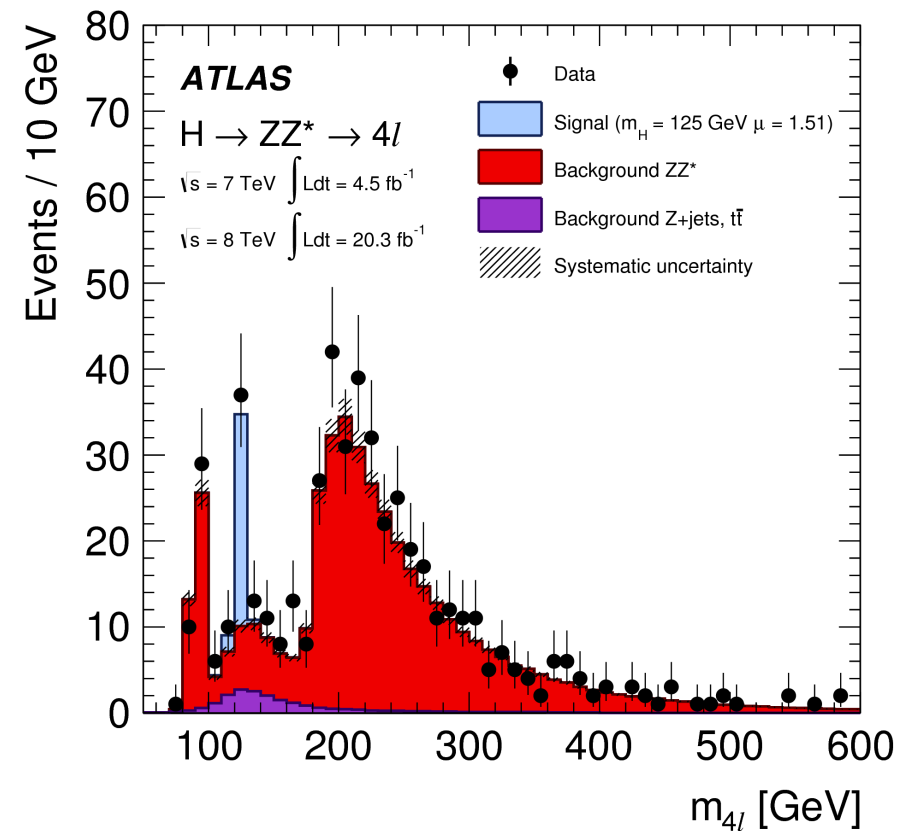
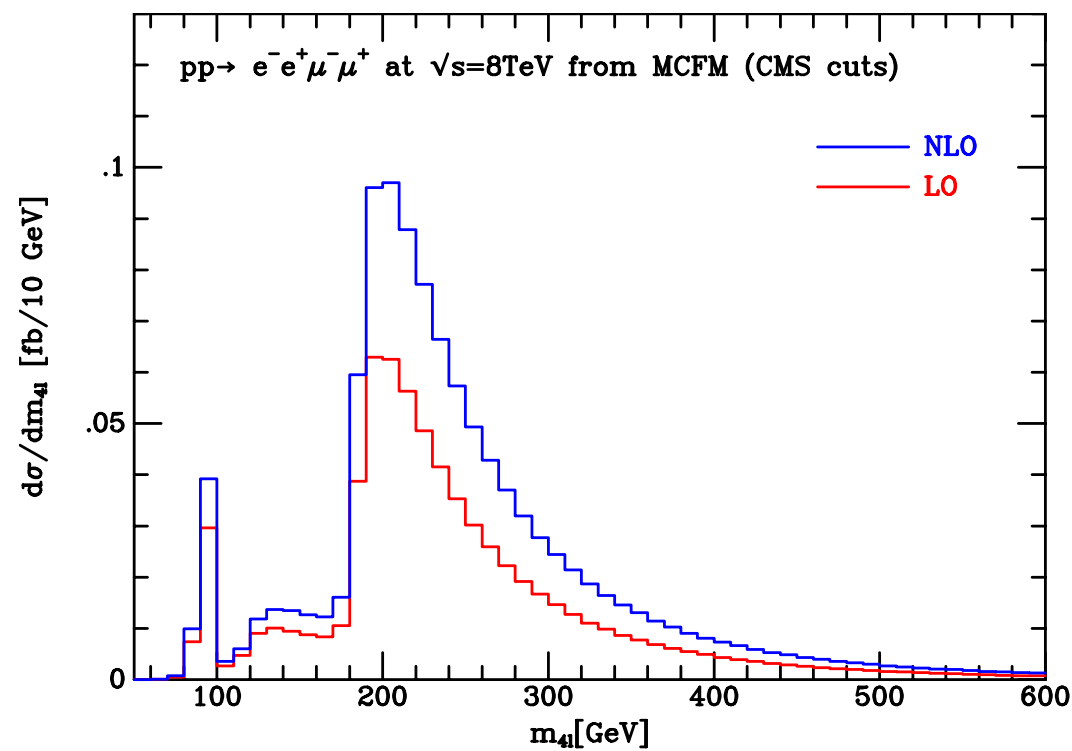
- MC<sup>2</sup>FM is a parton-level Monte Carlo program that computes hadron-collider cross sections at NLO [Campbell, RKE, Williams]
- Gives access to explicit final states, distributions.
- Implements analytic results for matrix elements, so fast and numerically stable.
- Flexible, freely distributed code, widely used in the community
- Theoretical predictions for more than 300 processes, (extensive use at Tevatron and LHC, (cited by > 650 experimental papers).
- Significant role as a catalyst for other theoretical efforts.
- Eight updates to the code in the last eight years.

# Vector boson pair production

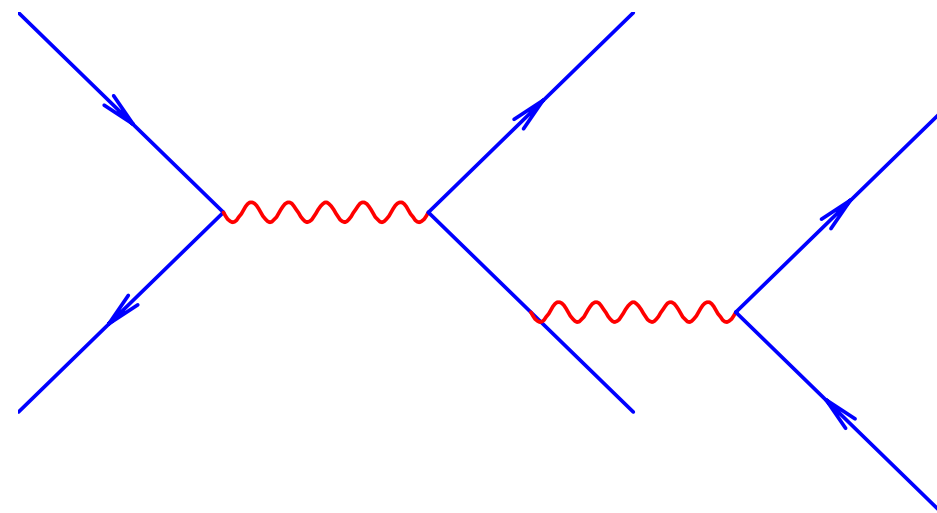
- For the final states that we are interested in, we go beyond the doubly resonant approximation.
- Z-peak coming from singly resonant diagrams, important check of resolution in search for Higgs boson.
- NLO includes  $gg \rightarrow ZZ$ , (but no Higgs yet, see later).



# Singly resonant contribution and Higgs discovery



- Relative size of peaks depends sensitively on the cuts

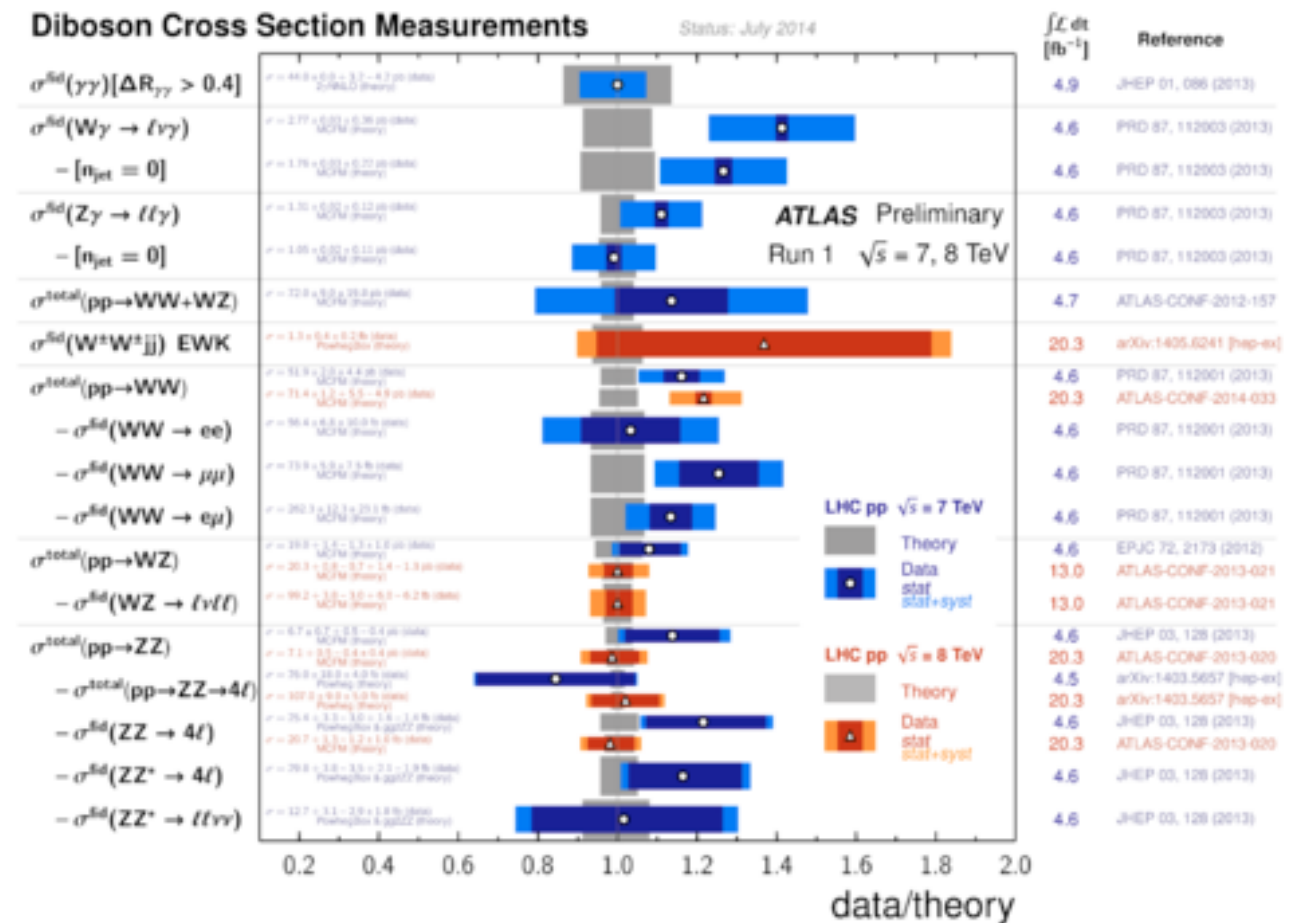




# Vector boson pair production

ATLAS results

- Growth of Boson pair cross section with energy is an important check of gauge structure.
- For  $W^+W^-$ , no discrepancy in fiducial cross section.
- Emphasizes the importance of going beyond total rates.



	ATLAS @ 8 TeV	$pp \rightarrow l^+ l^- \nu \bar{\nu}$	$pp \rightarrow H \rightarrow l^+ l^- \nu \bar{\nu}$	total
$e^+ \mu^- + e^- \mu^+$	$377.8^{+6.9}_{-6.8}(\text{stat.})^{+25.1}_{-22.2}(\text{syst.})^{+11.4}_{-10.7}(\text{lumi.})$	$332.4^{+4.7}_{-2.3}$	$9.8^{+0.0}_{-1.2}$	$342.2^{+4.7}_{-2.6}$
$e^+ e^-$	$68.5^{+4.2}_{-4.1}(\text{stat.})^{+7.7}_{-6.6}(\text{syst.})^{+2.1}_{-2.0}(\text{lumi.})$	$63.7^{+0.8}_{-0.4}$	$2.2^{+0.0}_{-0.2}$	$65.9^{+0.8}_{-0.4}$
$\mu^+ \mu^-$	$74.4^{+3.3}_{-3.2}(\text{stat.})^{+7.0}_{-6.0}(\text{syst.})^{+2.3}_{-2.1}(\text{lumi.})$	$69.3^{+0.9}_{-0.4}$	$2.4^{+0.0}_{-0.2}$	$71.7^{+0.9}_{-0.5}$

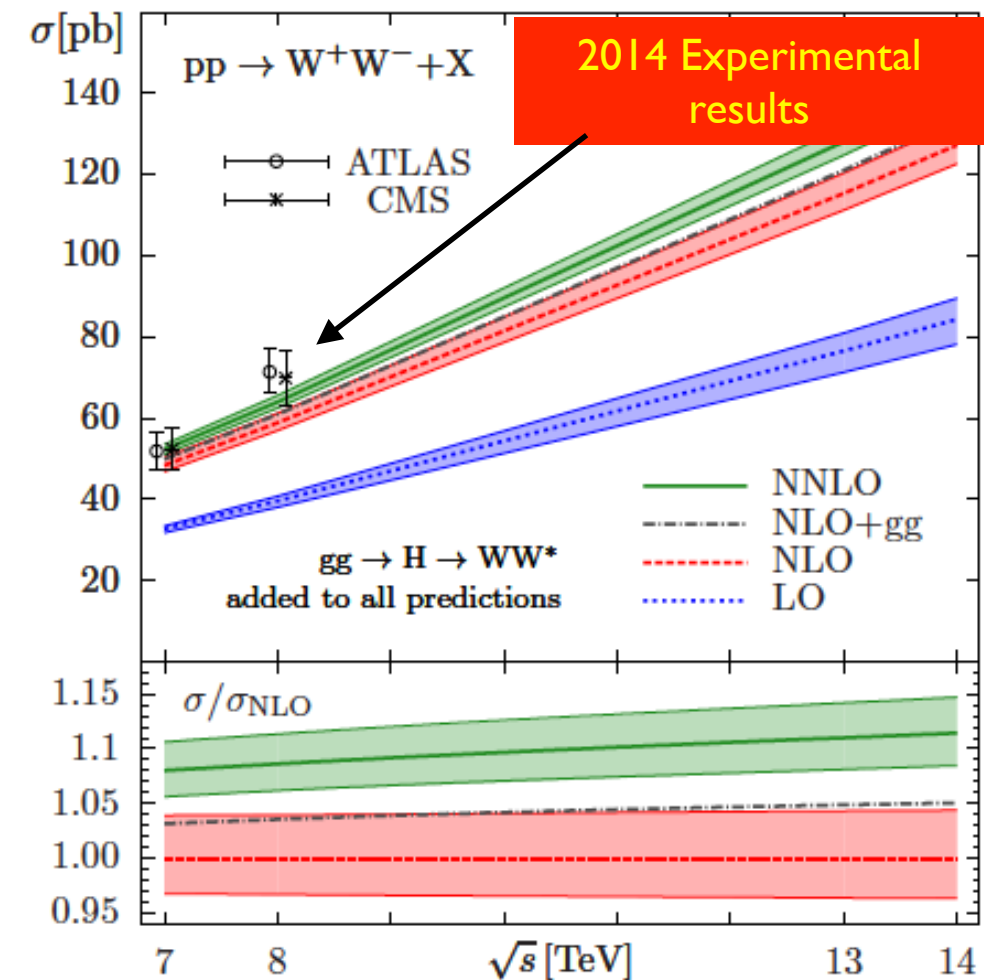
Monni, Zanderighi 1410.4745

MCfM results

Keith Ellis, W&C, 8/21/2015

# Necessity of NNLO

Gehrmann et al, 1408.5243



Einsweiler, Lepton Photon 2015

## Di-boson production: W<sup>+</sup>W<sup>-</sup> Production (CMS)

- Measure  $\sigma(\text{fid}) = 60.1 \pm 0.9$  (stat)  $\pm 3.2$  (exp)  $\pm 3.1$  (theo)  $\pm 1.6$  (lumi) pb
- Theory  $\sigma(\text{NNLO}) = 59.8 \pm 1.2$  pb
- Good agreement (expt  $\pm 8\%$ ), but NNLO calculations are really necessary.

# Heavy quark production

- Improvement of perturbative stability as we proceed to NLO.
- Results apply to top, bottom, and perhaps charm production.
- State of the art until Czakon et al. 1303.6254

## THE TOTAL CROSS SECTION FOR THE PRODUCTION OF HEAVY QUARKS IN HADRONIC COLLISIONS

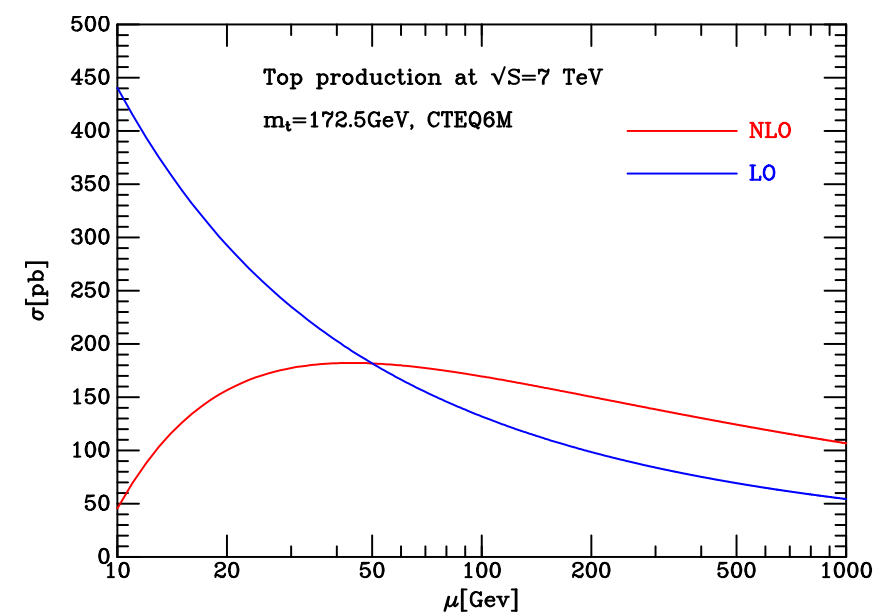
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Received 6 January 1988



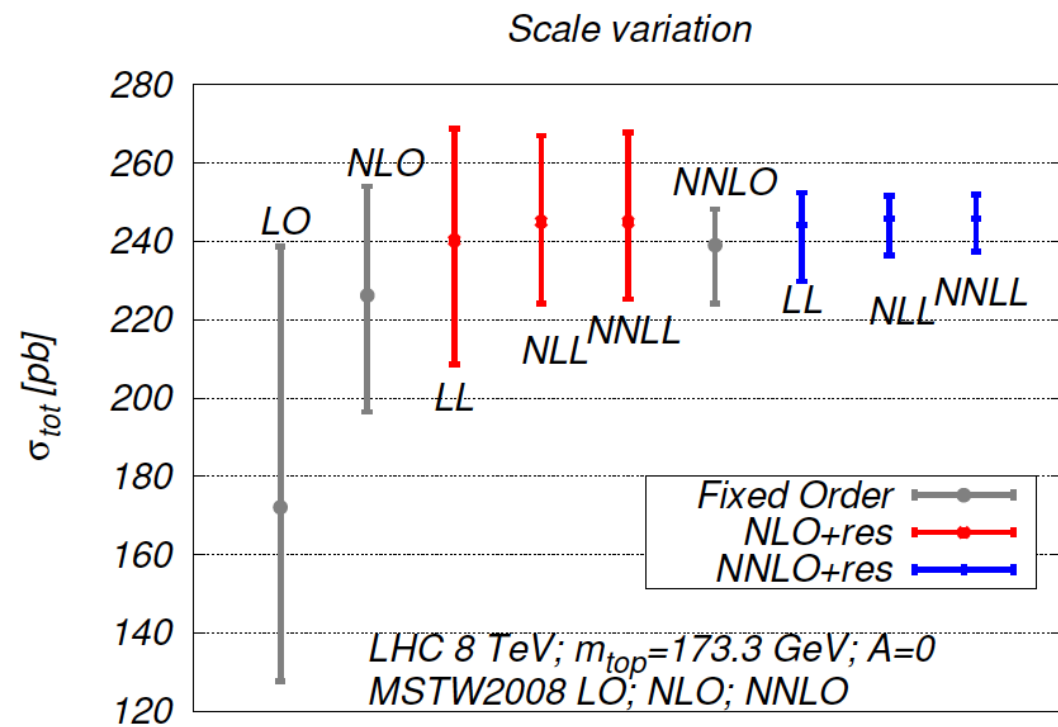
Paolo Nason

Sally Dawson



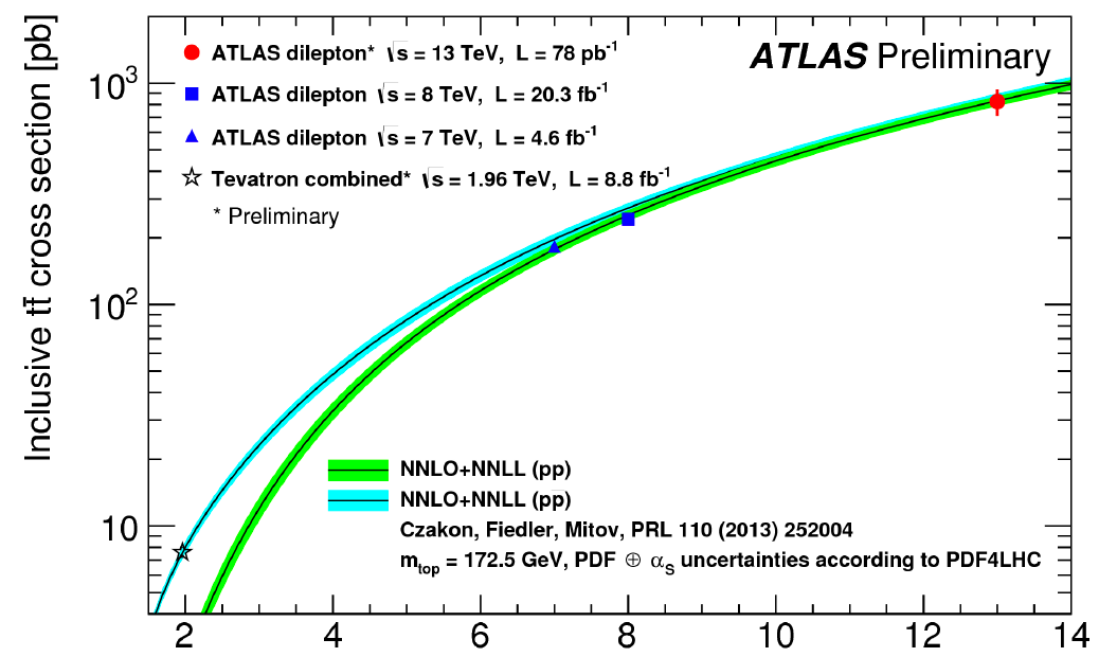
# Rates for top production

- Progression of results as higher order terms were included.
- Emphasizes the importance of a true (N)NLO calculation.
- NNLO results beautifully confirmed by results at 7 and 13 TeV.



Czakon et al, 1305.3892

ATLAS-CONF-2015-033

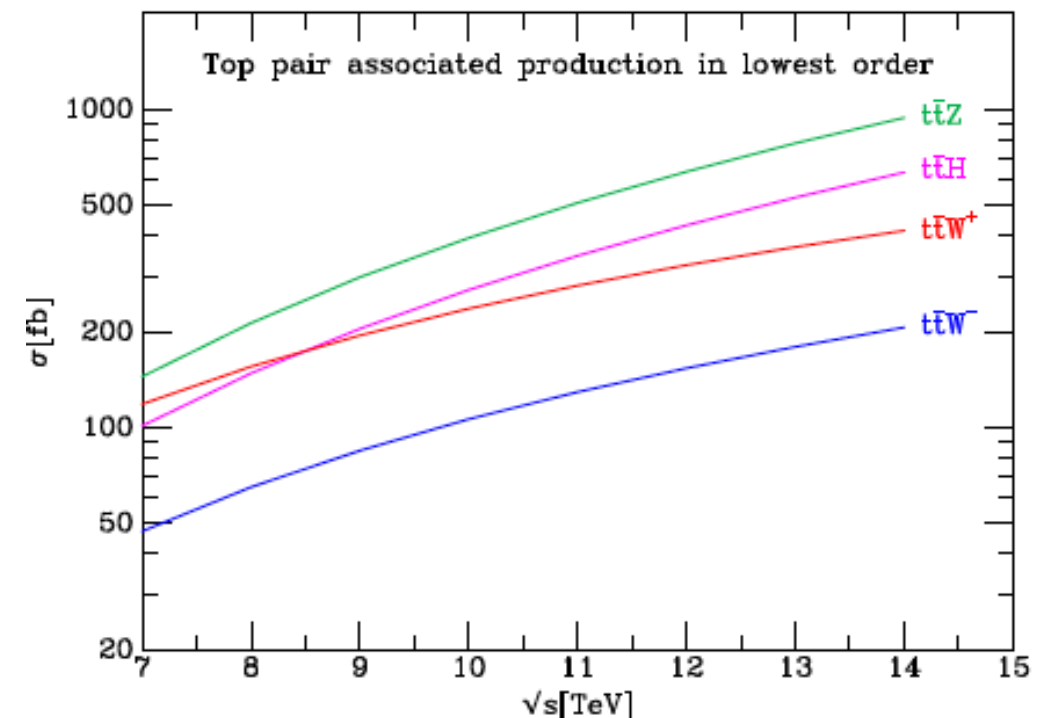
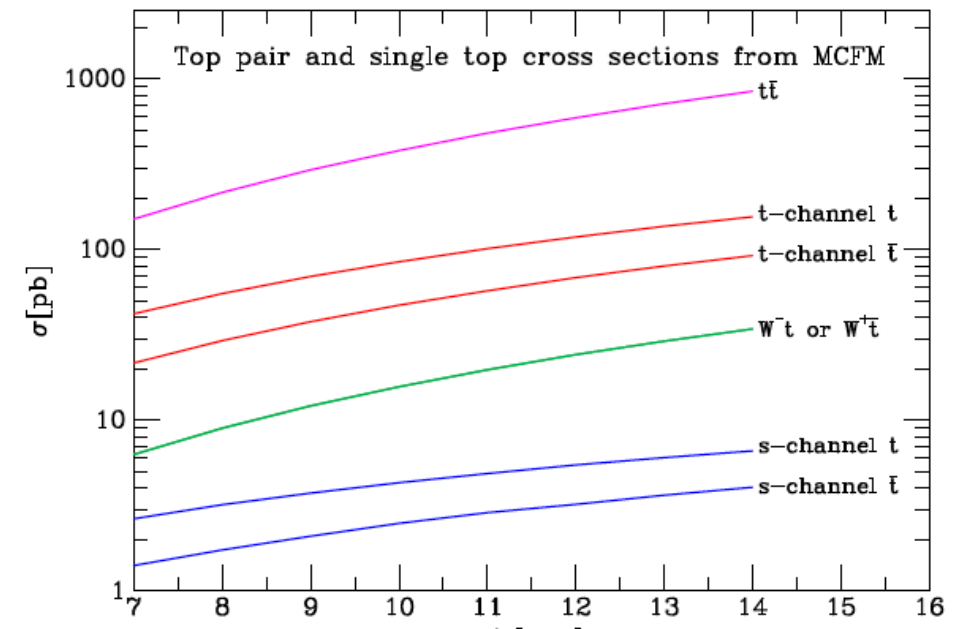


Keith Ellis, W&C, 8/21/2015

# Top, from signal to calibration to background.

- Top production grows rapidly with energy.
- Plethora of top-related processes. Top pair, single top,  $t\bar{t}V$ ,  $tV$  ( $V$ =electroweak boson), Top pair + 1,2,3,4, jets....
- We need to find a framework to include these processes, which is simpler than calculating the full final state.

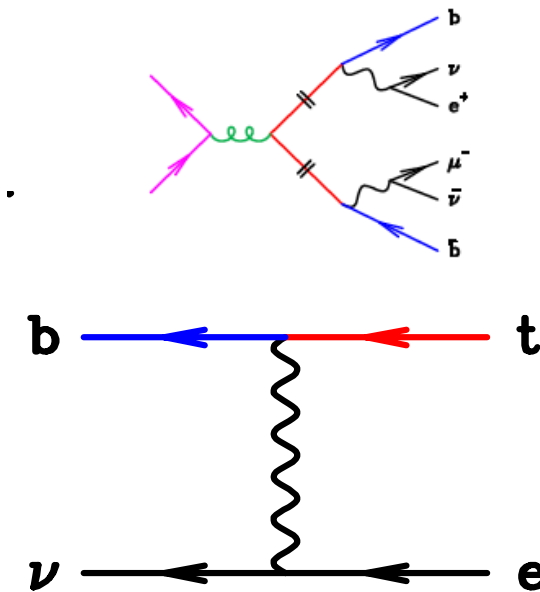
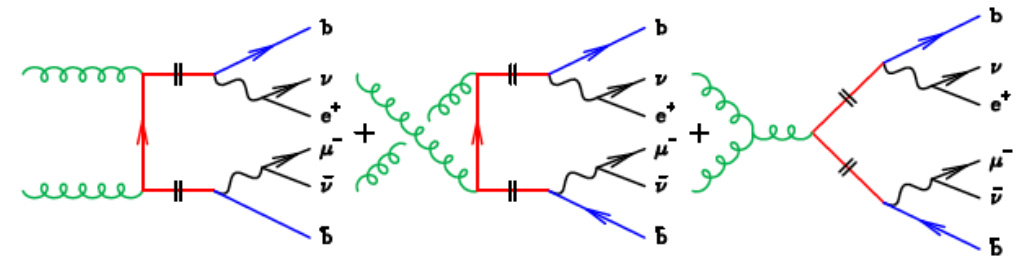
$$pp \rightarrow W^+W^-b\bar{b} \rightarrow \nu_e e^+ \mu^- \bar{\nu}_\mu b\bar{b}$$



# Practical proposal for top-related processes

Campbell, RKE 1204.1503

- Treat top quark as being on their mass-shells, but keep all spin correlations.
- For most variables the on-shell approximation will be smeared by the finite energy resolution of the detector.
- Since the coupling to the W is left-handed, it is actually easier to keep spin correlations, than to drop them.

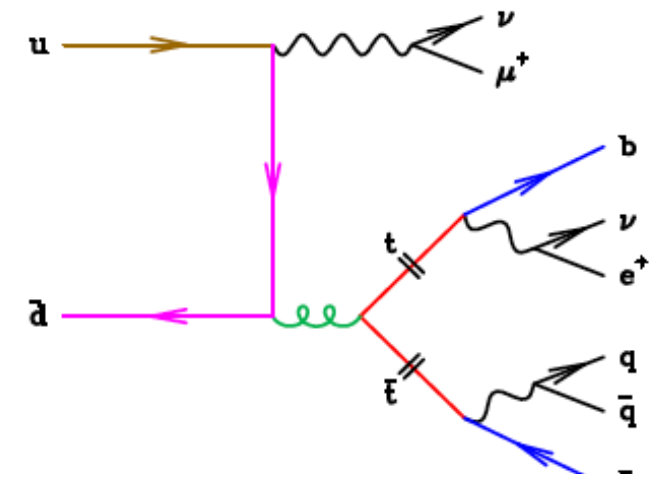


$$\begin{aligned} & \langle \nu | \gamma^\mu \gamma_L | e \rangle \times \bar{u}(b) \gamma_\mu \gamma_L (t\!\!\!/\ + m_t) \dots \\ &= 2 \bar{u}(b) | \nu \rangle \times [e | (t\!\!\!/\ + m_t) \dots \end{aligned}$$



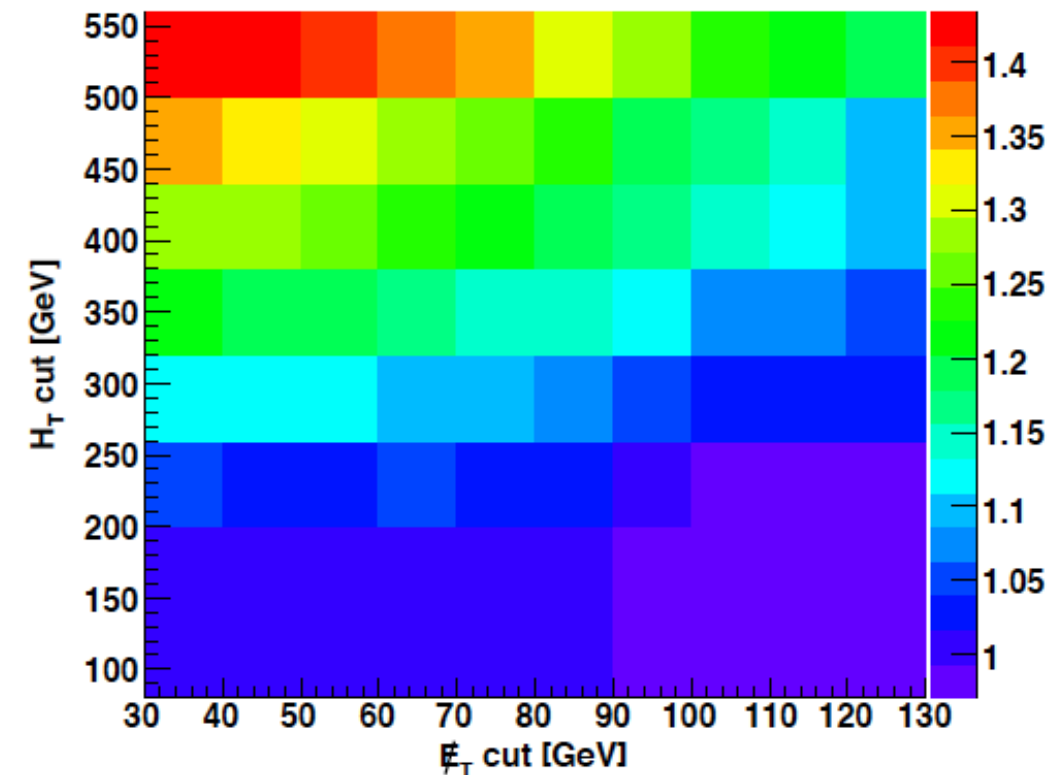
## Example: $ttW$

- $ttW$  is one process that can lead to same-sign leptons, missing energy and b quarks.
- This signature is common in BSM searches.
- Currently same sign di-lepton analyses must rely on theory to assess backgrounds.
- Other SM backgrounds,  $W^\pm Z$ ,  $ZZ$ ,  $W^\pm W^\pm$ ,  $WWW$ ,  $W^+W^-Z$ ,  $ZZZ$ ,  $ttZ$



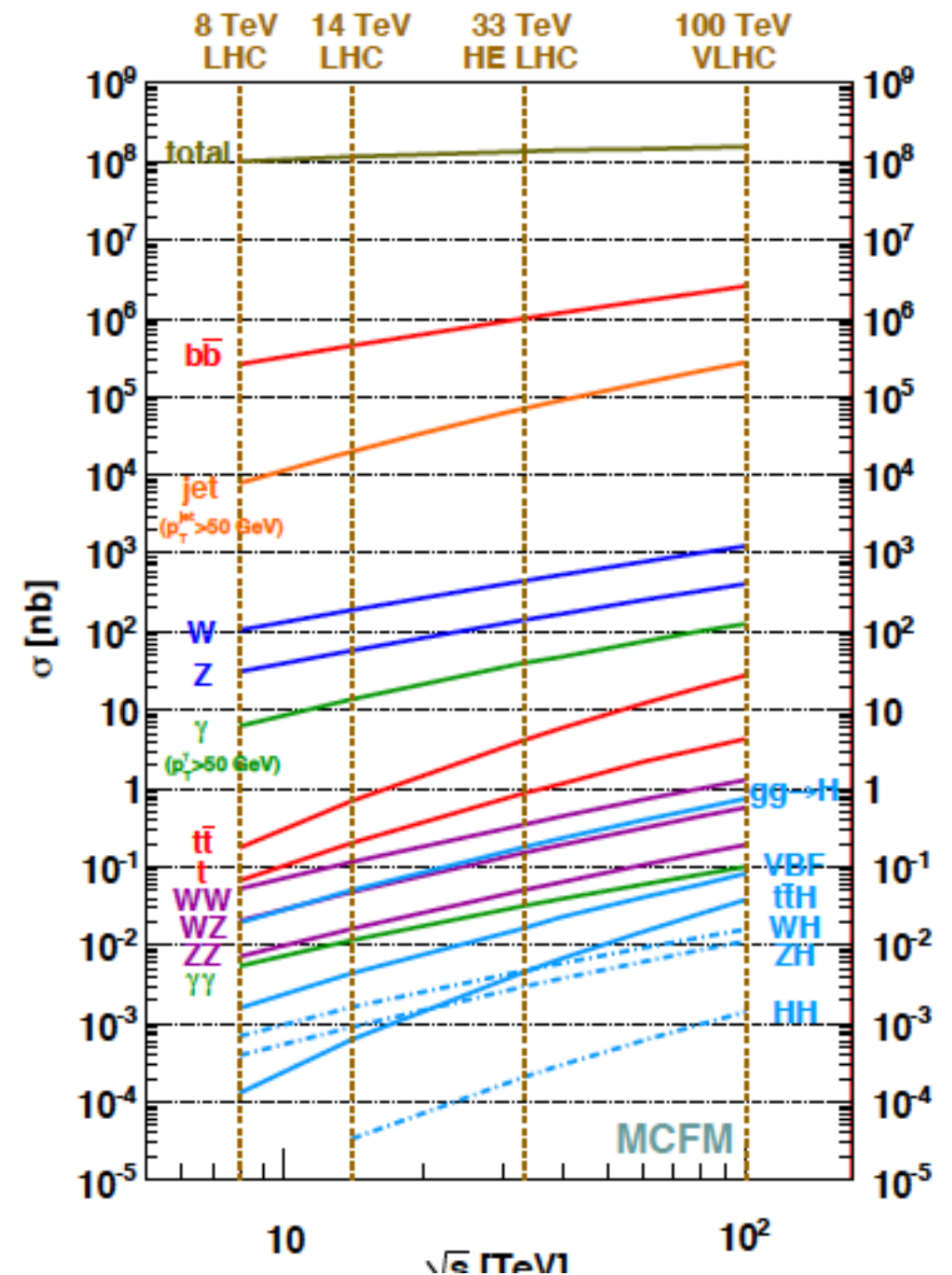
$$H_T = \sum_i p_T(\text{jet } i)$$

$$K = \sigma_{\text{NLO}}^{++} / \sigma_{\text{LO}}^{++}$$



# MC2FM-Looking to the future

- Open MP version v7.0
- Release of MPI version.
- Working on first inclusion of NNLO for simple DY type processes — with a view to introducing more complicated processes.



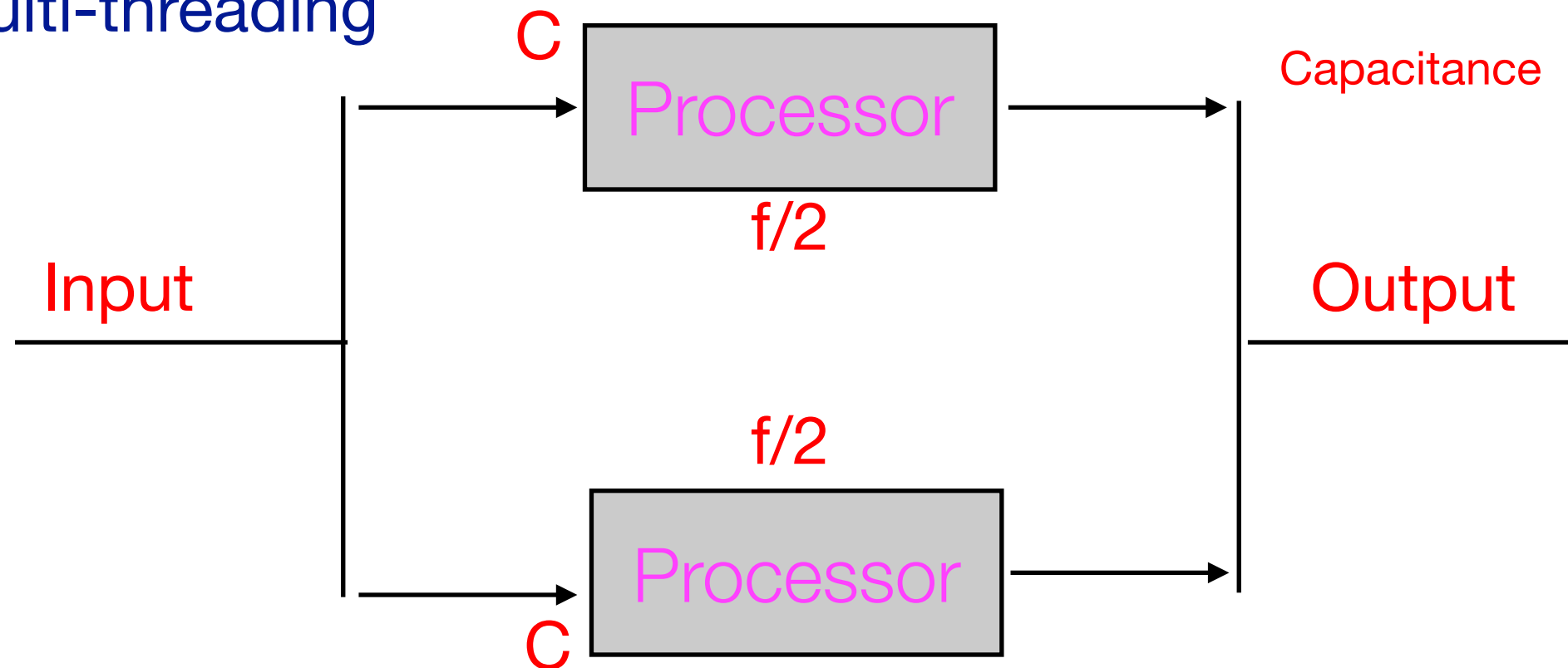


# MCFM and Open Multi-processing

- \* Growth of power/performance requires multi-threading

$$P = CV^2 f$$

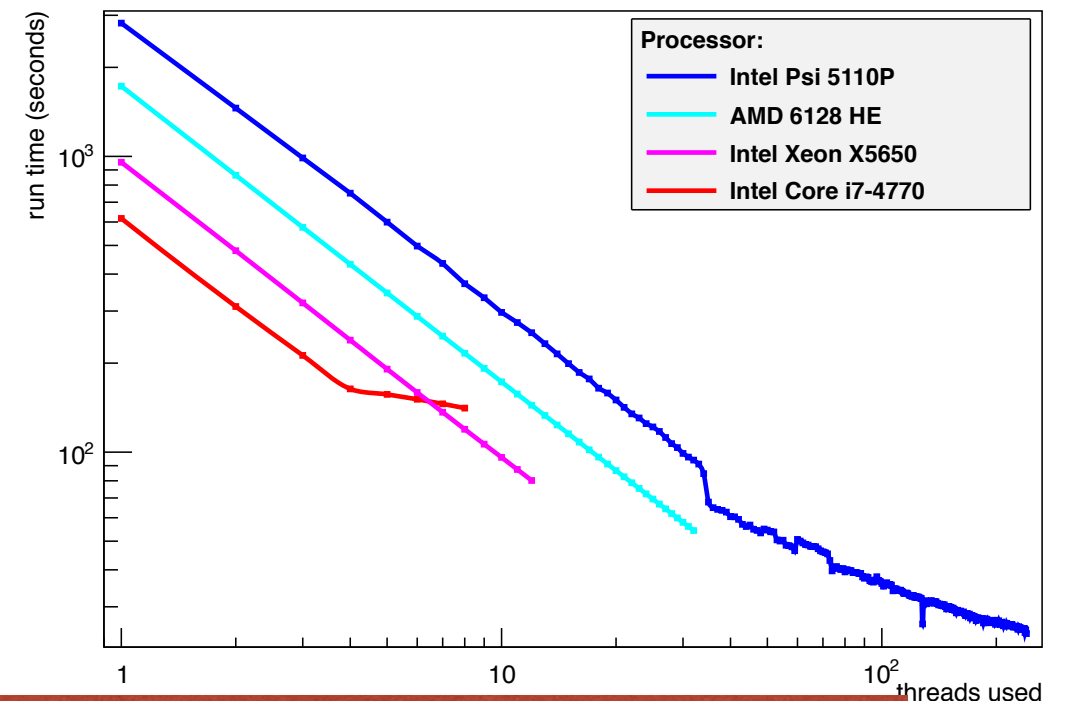
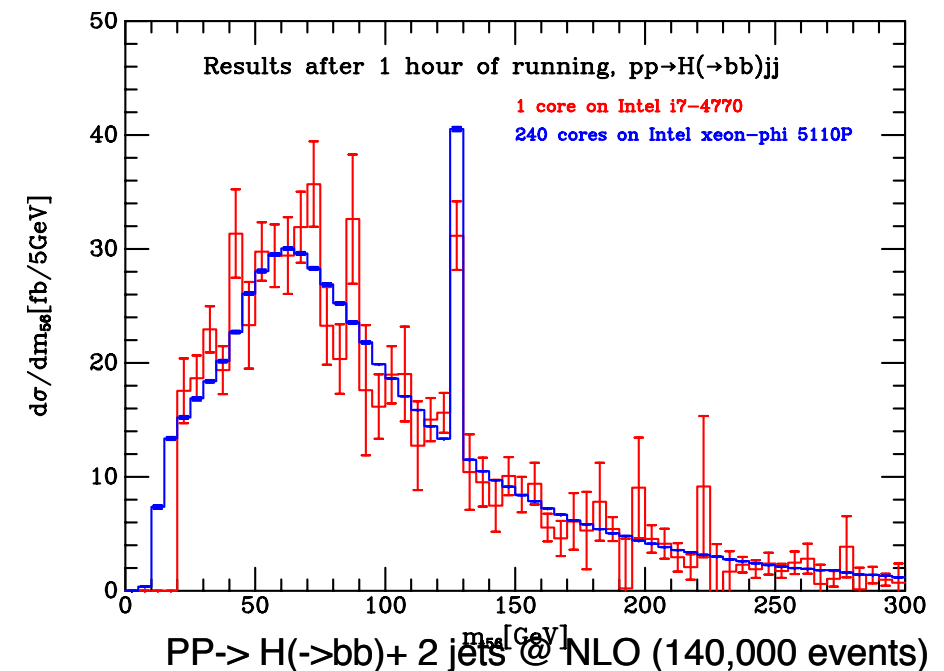
Power                      Voltage  
Capacitance              Clock speed



- \* By putting, say, two cores in parallel,  $C \rightarrow 2C$ ,  $f \rightarrow f/2$ ,  $V \rightarrow V/2$  at constant performance.
- \* Continued validity of Moore's law thus requires innovation in software, to deal with multi-threading in hardware.

# MCFCM and Open Multi-processing

- OpenMP offers standardized way of exploiting multithreading.
- e.g. standard option for gfortran and intel compilers.
- Non destructive of the single thread code, (compiler directives interpreted as comments without openMP flag).
- Full statistics contributes to the adaptation of the VEGAS grid



Speedup of 98x with 128 cores

# One loop diagrams: NLO revolution

# NLO pre-revolutionary techniques

- The classical paradigm for the calculation of one-loop diagrams was established in 1979.
- Complete calculation of one-loop scalar integrals.
- Reduction of tensor integrals to scalar integrals.

$$\int d^n l \frac{l^\mu}{(l^2 - m_1^2 + i\varepsilon)((l+p)^2 - m_2^2 + i\varepsilon)}$$

Nuclear Physics B153 (1979) 365–401  
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## SCALAR ONE-LOOP INTEGRALS

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*Institute for Theoretical Physics\*, University of Utrecht, Netherlands*

Received 16 January 1979

Nuclear Physics B160 (1979) 151–207  
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## ONE-LOOP CORRECTIONS FOR $e^+e^-$ ANNIHILATION INTO $\mu^+\mu^-$ IN THE WEINBERG MODEL

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*Institute for Theoretical Physics, University of Utrecht, Utrecht, The Netherlands*

Received 22 March 1979

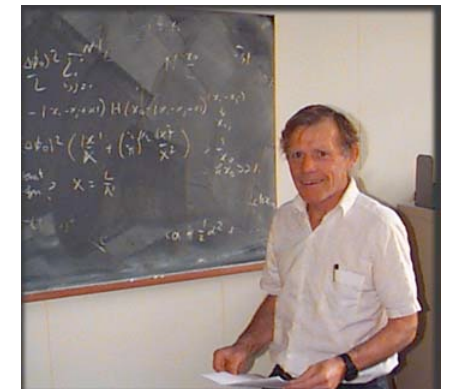
# NLO revolution: Basis set of scalar integrals

- Any one-loop amplitude, with no matter how many legs, can be written as a linear sum of box, triangle, bubble and tadpole integrals

$$\mathcal{A}_N(\{p_i\}) = \sum d_{ijk} \text{box} + \sum c_{ij} \text{triangle} + \sum b_i \text{bubble} + \sum_i a_i \text{tadpole}$$

- In the context of NLO calculations scalar higher point functions can be expressed as a sum of box integrals.
- This result present in the 1965 thesis of Donald Melrose.
- In short, if we know the box, triangle, bubble and tadpole integrals, and their coefficients, we know everything.

Donald Melrose

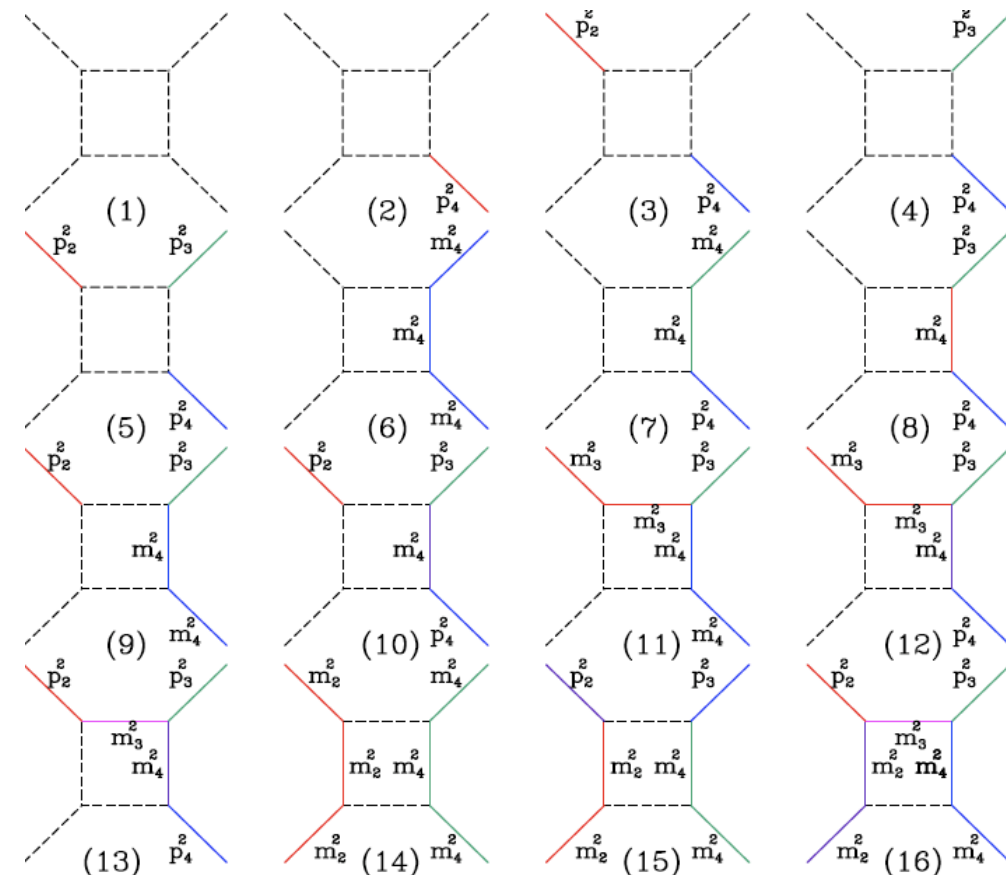


# QCDLoop: Basis set of 16 divergent box integrals



RKE,Zanderighi 0712.1851

- 't Hooft and Veltman's integrals contain internal masses, however in QCD many lines are approximately massless.
- The consequent soft and collinear divergences are regulated by dimensional regularization.
- Invention of algorithm that defines the basis set for box integrals.
- Analytic and numerical results for 16 divergent box integrals.
- QCDLoop completely solves the problem of one loop integrals.
- <http://qcdloop.fnal.gov>



Dashed lines are massless, line of the same color have same virtuality and/or mass

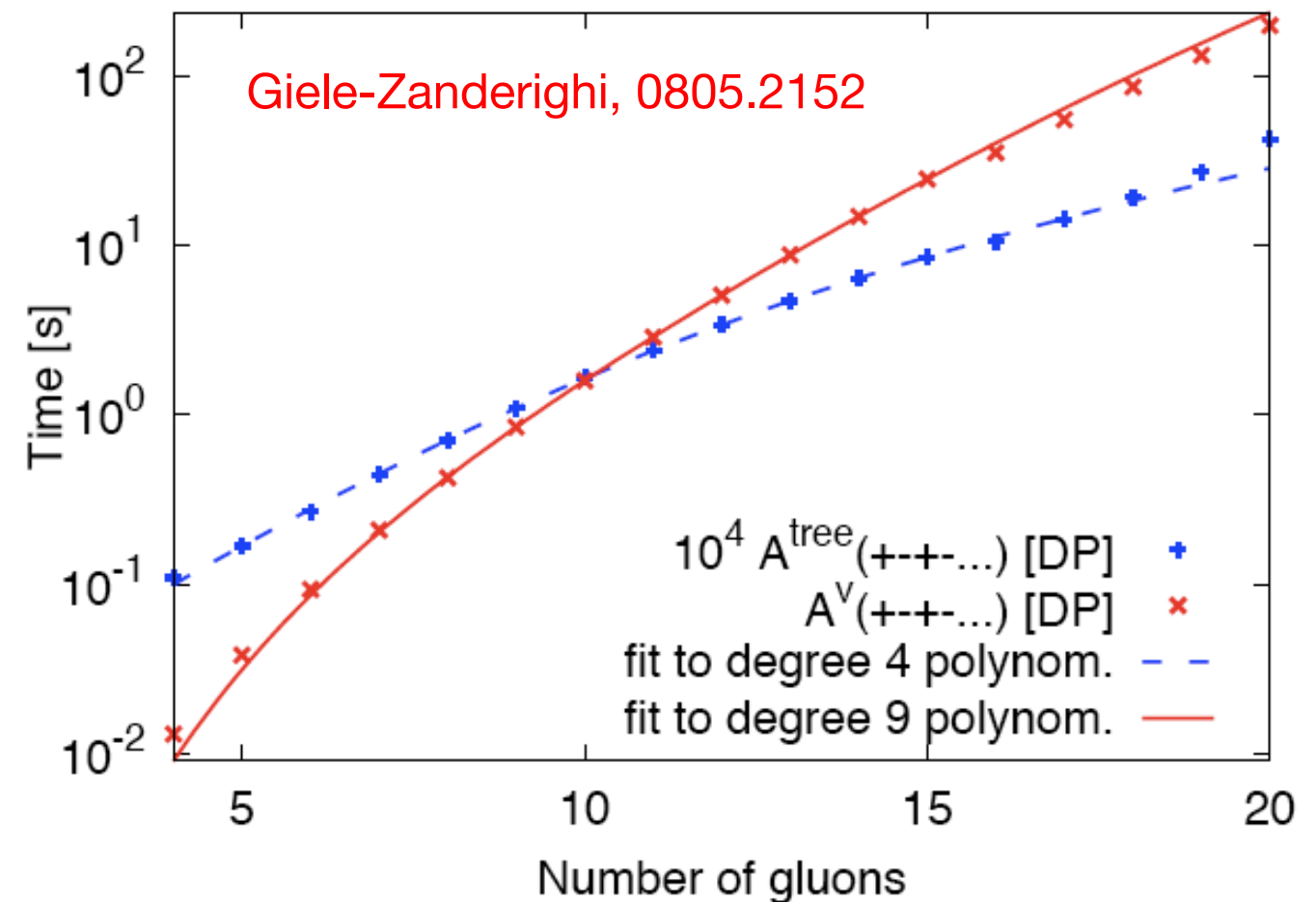
# Other revolutionaries: Unitarity for 1-loop diagrams

Techniques for determining the coefficients of the loop integrals

- Important steps include:-
- First modern use of the idea [Bern,Dixon,Kosower](#)
- Cuts w.r.t. loop momenta to give box coefficients directly [Britto,Cachazo and Feng](#)
- OPP reduction scheme [Ossola, Papadopoulos,Pittau](#)
- Combining the OPP procedure with unitarity [RKE, Giele,Kunszt](#)
- D-dimensional unitarity. [Giele, Kunszt, Melnikov](#)

# One-loop calculations of pure gluon amplitudes

- Time to calculate one-loop amplitude scales as  $N^9$  as expected. For small numbers of legs,  $N=4,5,6$  the times are of the order of milliseconds.
- d-dimensional unitarity is a disruptive technology.
- Semi-numerical methods are the basis of most automatic procedures for determining one-loop amplitudes.



4g: RKE, Sexton 1985  
5g: Bern, Dixon, Kosower, 1993  
6g: RKE, Zanderighi, 2006

Walter Giele

Giulia Zanderighi



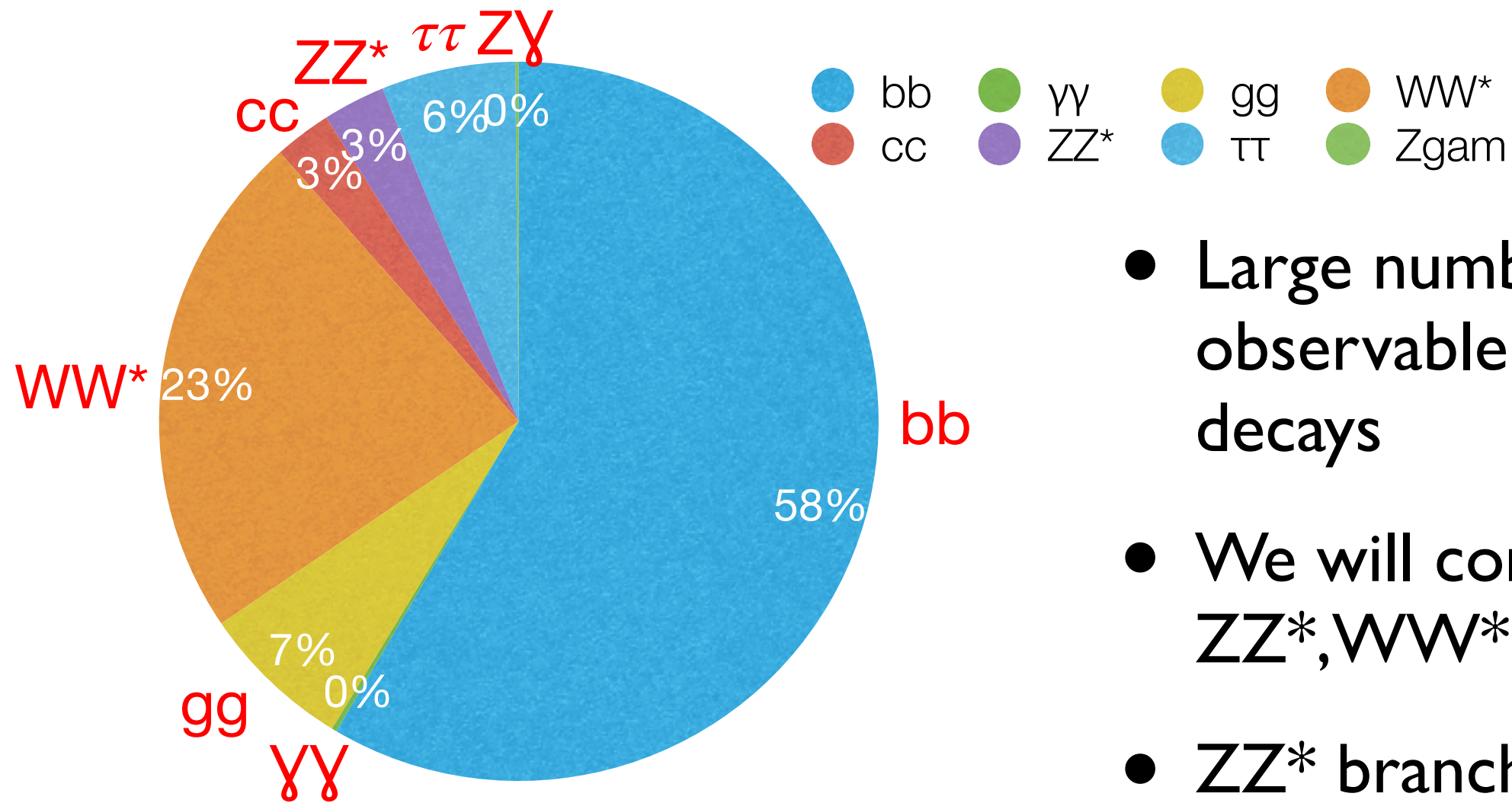


## Subsequent automatic NLO programs

- Fully automatic procedures.
  - Madgraph5\_aMC@NLO [405.0301]
  - Helac-1Loop [502.01521]
  - Go-Sam [404.7096]
- Approaches for greater number of legs of a less automatic nature.
  - Blackhat-Sherpa [310.2808]
  - Njet [312.7140]

# The Higgs boson and interference

# How can we probe a 4 MeV width for the Higgs?



- Large number of observable SM Higgs decays
- We will consider ZZ\*, WW\*.
- ZZ\* branching ratio is 3%, (but before BR to observable mode).
- $\Gamma_H^{\text{SM}} \approx 4 \text{ MeV}$ , c.f. jet resolution  $\sim 1 \text{ GeV}$ .

Particle	Width[MeV]	Lifetime[s]
$t$	$\sim 1,300$	$\sim 5 \times 10^{-25}$
$W$	$\sim 2,000$	$\sim 3 \times 10^{-25}$
$Z$	$\sim 2,500$	$\sim 2.6 \times 10^{-25}$
$h$	$4.21 \pm 0.16$	$\sim 1.65 \times 10^{-22}$
$b$	$4.4 \times 10^{-10}$	$\sim 1.5 \times 10^{-12}$

## Rescaling properties of the cross section on the peak

- In the narrow width approximation

$$\sigma(i \rightarrow H) \times BR(H \rightarrow X) = |M(i \rightarrow h)|^2 \frac{\Gamma(h \rightarrow X)}{\Gamma_h} \sim \frac{g_i^2 g_f^2}{\Gamma_h}$$

- Measurements on the Higgs peak, are only sensitive to the ratio,

$$\frac{g_i^2 g_f^2}{\Gamma_h}$$

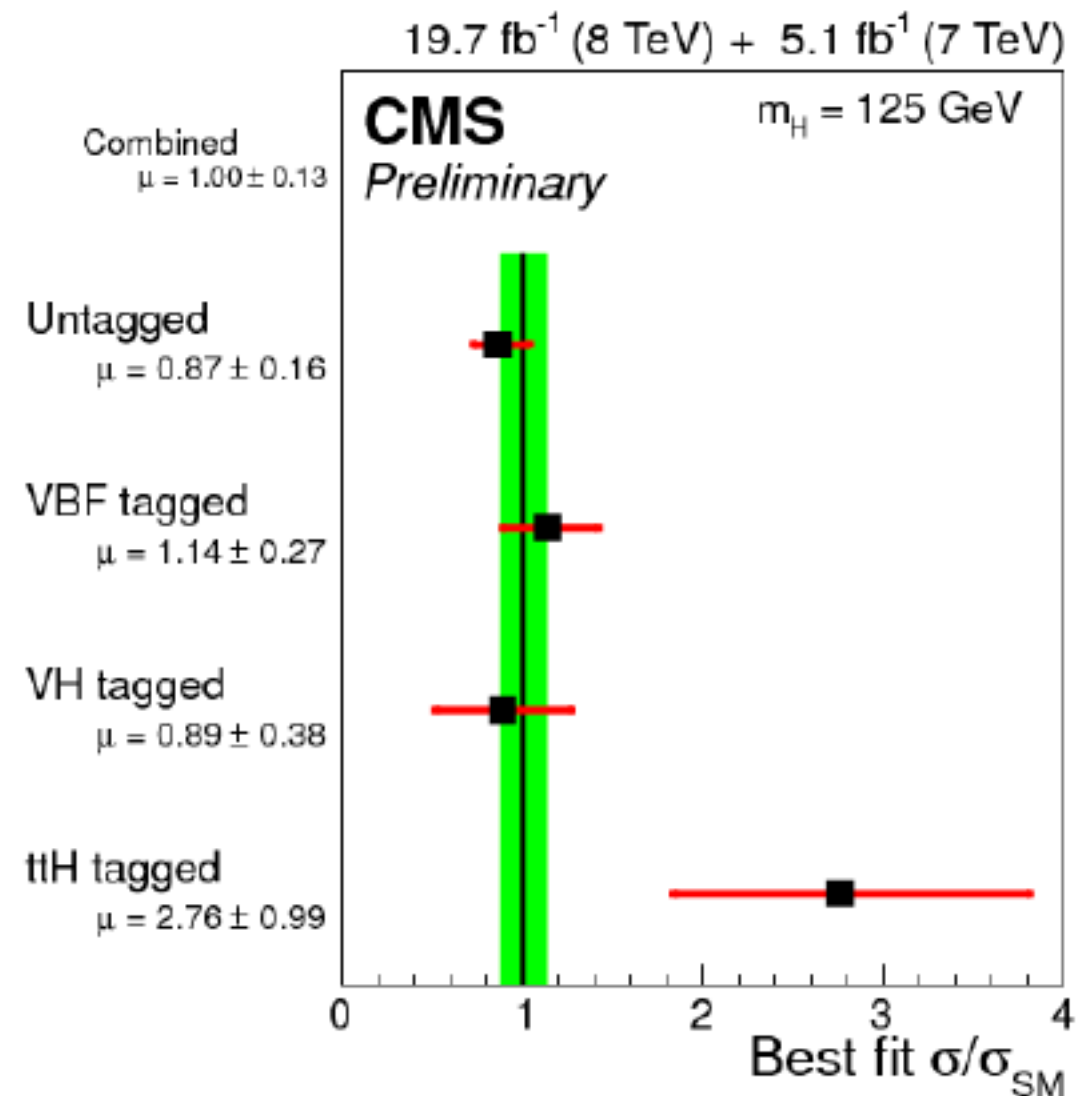
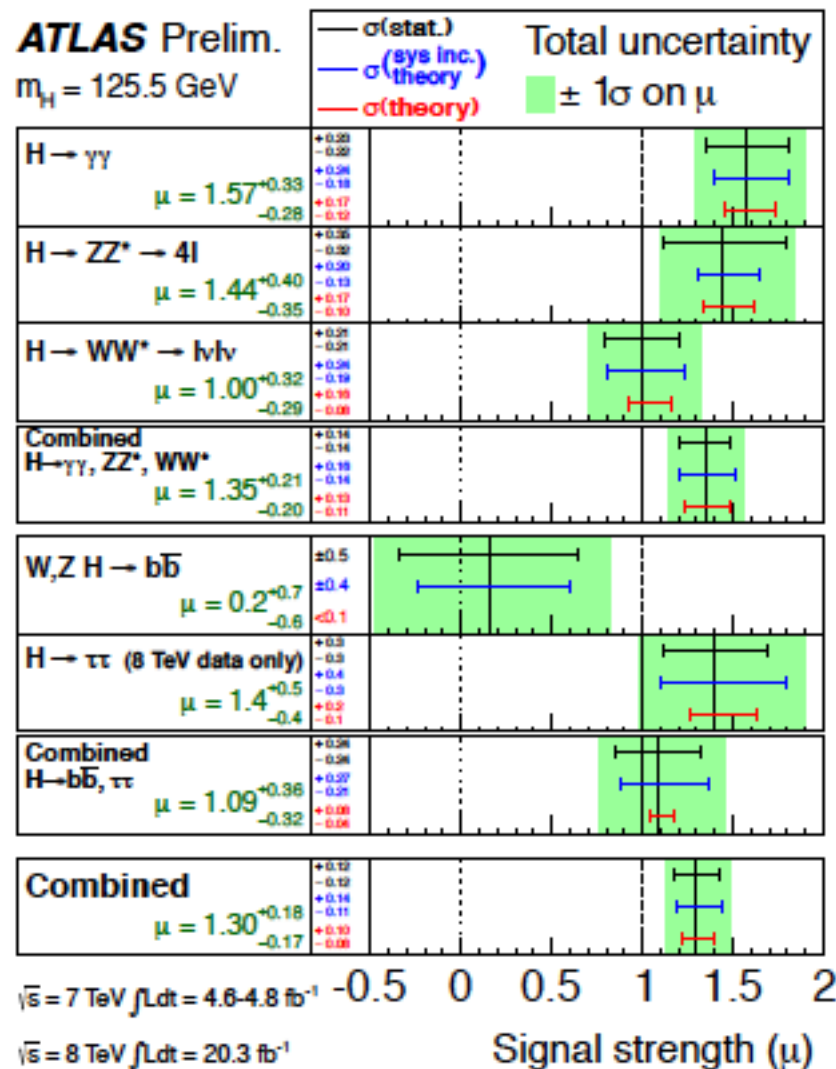
- Performing the rescaling by  $\kappa$  leaves the on-shell rate unchanged.

$$g_i \rightarrow \kappa g_i$$

$$g_f \rightarrow \kappa g_f$$

$$\Gamma_H \rightarrow \kappa^4 \Gamma_H$$

# Signal strength measurements



- Signal strength measurements, (that assume a value for the total width), confirm that  $g_i^2 g_f^2 / \Gamma_h$  is close to its standard model value (with  $\sim 20\%$  errors)

## Narrow width approximation for Higgs production

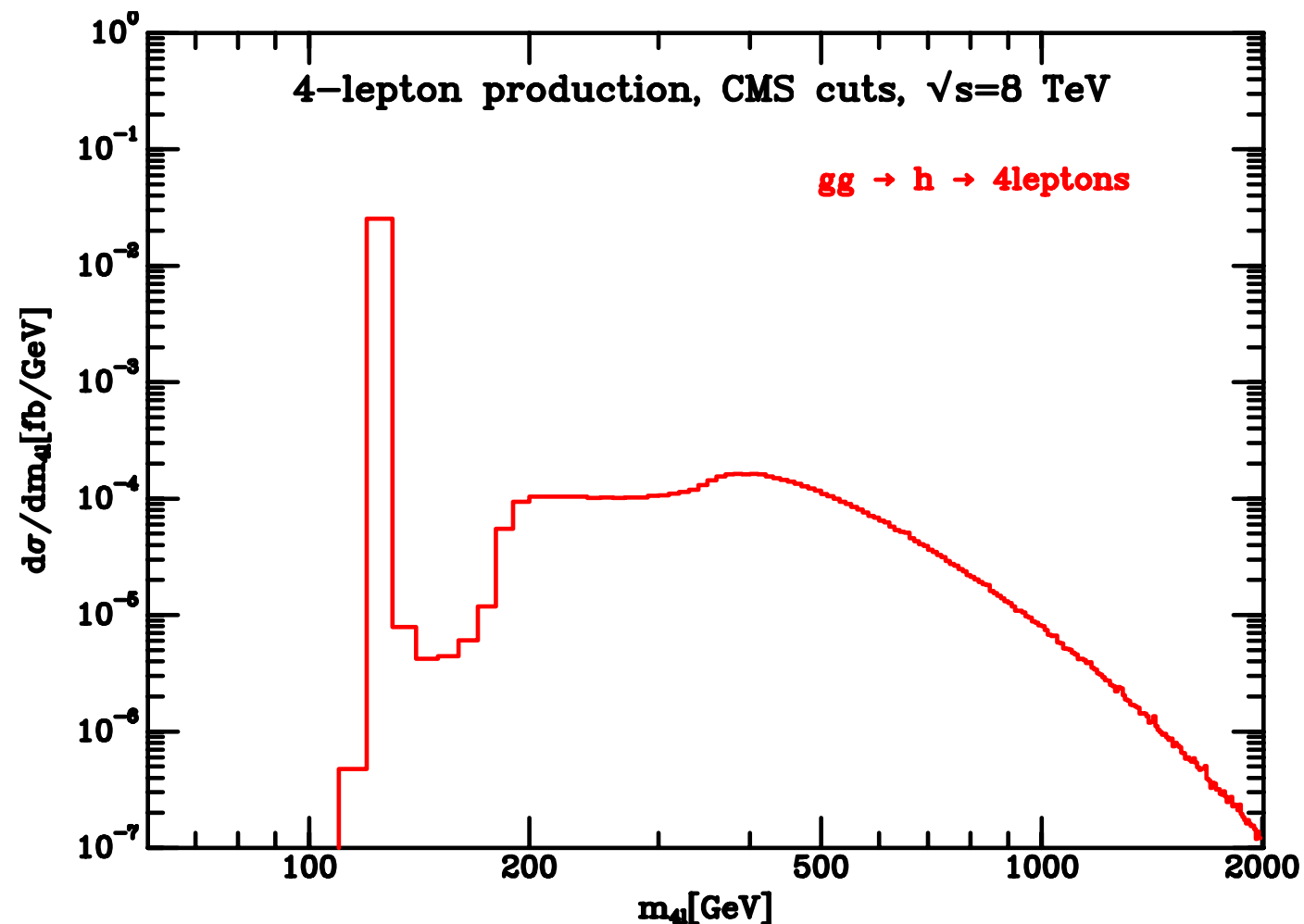
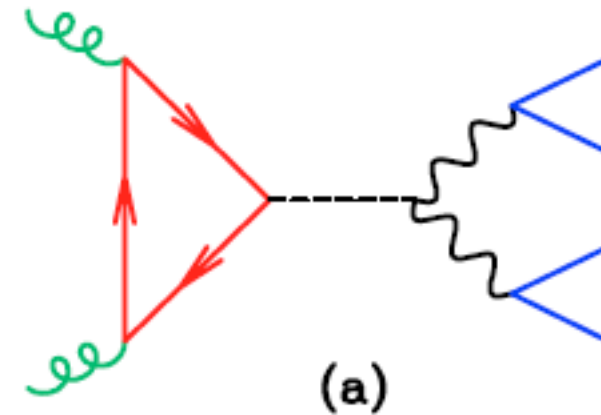
$$\frac{1}{(\hat{s} - M_h^2)^2 + M_h^2 \Gamma_h^2} \approx \frac{\pi}{M_h \Gamma_h} \delta(\hat{s} - M_h^2) .$$

- For the standard model Higgs,  $\Gamma/M_h = 1/30,000$  so narrow width approximation should apply.....

# Narrow width approximation for Higgs boson

- How can it fail?
  - $\Gamma_H / M_H = 1/30,000$
- It fails spectacularly for  $gg \rightarrow H \rightarrow ZZ^{(*)} \rightarrow e^-e^+\mu^-\mu^+$ .

Kauer, Passarino, arXiv:1206.4803
- At least 10% of the cross section comes from  $m_{4l} > 130 \text{ GeV}$ .



## Interference in $pp \rightarrow ZZ \rightarrow e^-e^+\mu^-\mu^+$

$$p + p \rightarrow H \rightarrow ZZ$$

$\rightarrow \mu^- + \mu^+$

$\rightarrow e^- + e^+ .$

$$p + p \rightarrow Z/\gamma^* + Z/\gamma^*$$

$\rightarrow \mu^- + \mu^+$

$\rightarrow e^- + e^+$

- We cannot consider the Higgs process alone.
- Both interfering and non-interfering backgrounds.

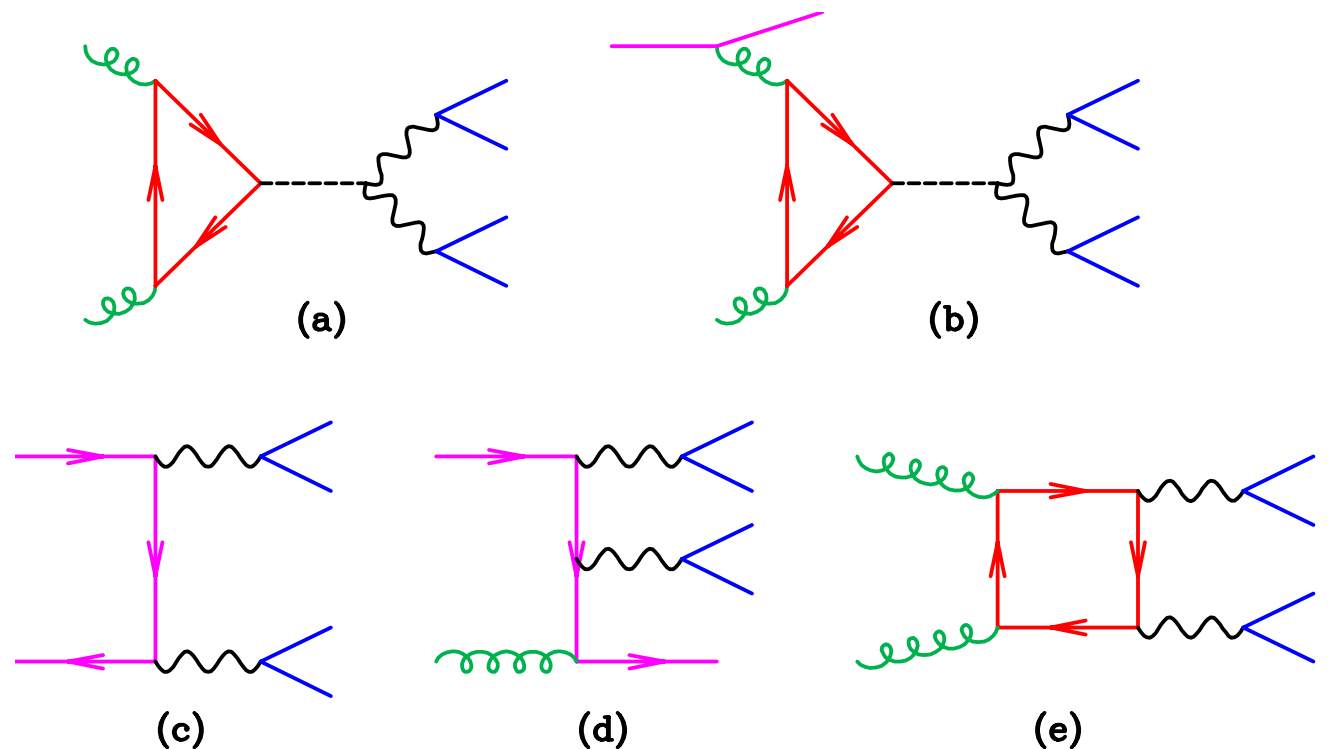


# $pp \rightarrow e^- e^+ \mu^- \mu^+$ in the standard model

- Mishmash of orders in perturbation their

$(a) : g(-p_1) + g(-p_2) \rightarrow H \rightarrow e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$
$(b) : q(-p_1) + g(-p_2) \rightarrow H \rightarrow e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s^3 e^4)$
$(c) : q(-p_1) + \bar{q}(-p_2) \rightarrow e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(e^4)$
$(d) : q(-p_1) + g(-p_2) \rightarrow e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6) + q(p_7)$	$O(g_s e^4)$
$(e) : g(-p_1) + g(-p_2) \rightarrow e^-(p_3) + e^+(p_4) + \mu^-(p_5) + \mu^+(p_6)$	$O(g_s^2 e^4)$

- Representative diagrams are:-
- (a) and (e), (b) and (d) can interfere.
- (b-d) interference does not overwhelm (a-e)

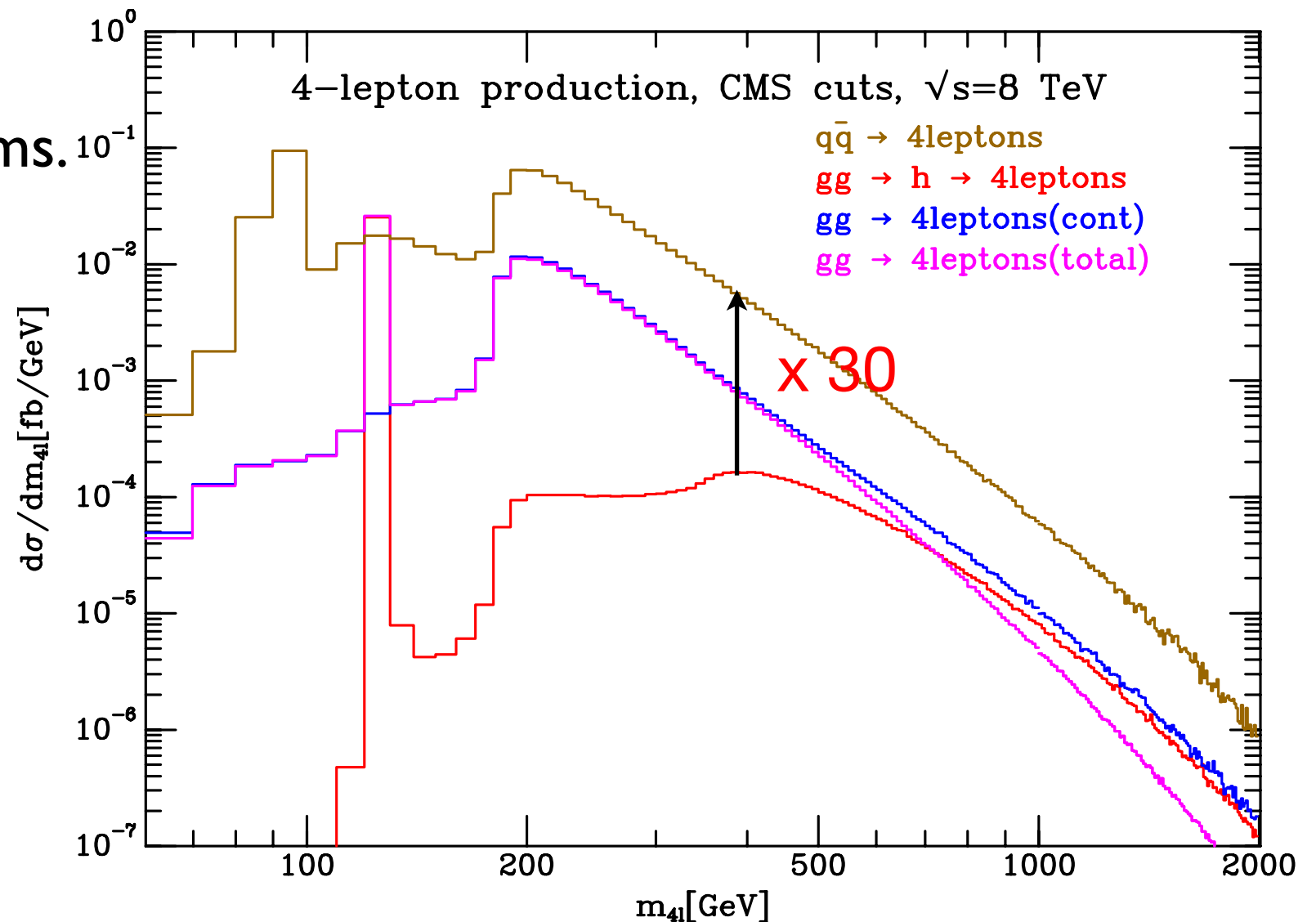


# The big picture @ 8TeV

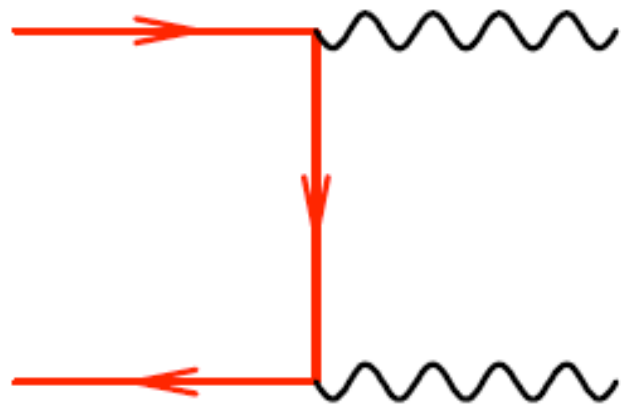
$$\begin{aligned} p_{T,\mu} &> 5 \text{ GeV}, \quad |\eta_\mu| < 2.4, \\ p_{T,e} &> 7 \text{ GeV}, \quad |\eta_e| < 2.5, \\ m_{ll} &> 4 \text{ GeV}, \quad m_{4\ell} > 100 \text{ GeV}. \end{aligned}$$

CMS cuts  
CMS PAS HIG-13-002

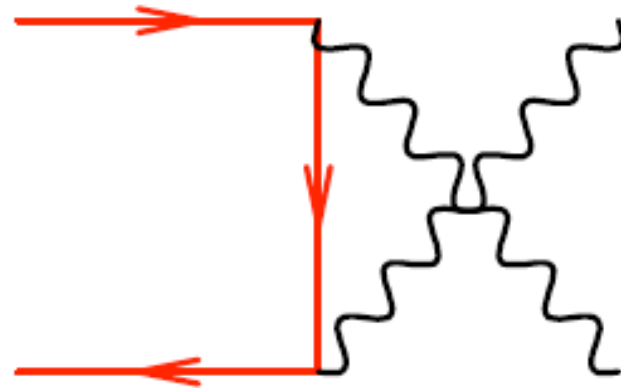
- Peak at Z mass due to singly resonant diagrams.
- Interference is an important effect off-resonance.
- Destructive at large mass, as expected.
- With the standard model width,  $\Gamma_H$ , challenging to see enhancement/deficit due to Higgs channel.



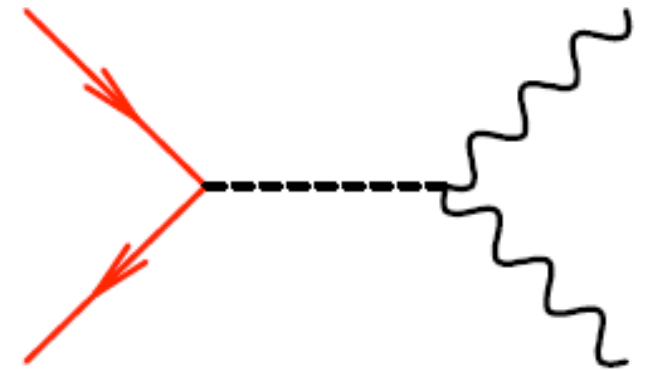
## Higgs being Higgs



$$a_2 E^2 + (b_1 + a_1) m_t E$$



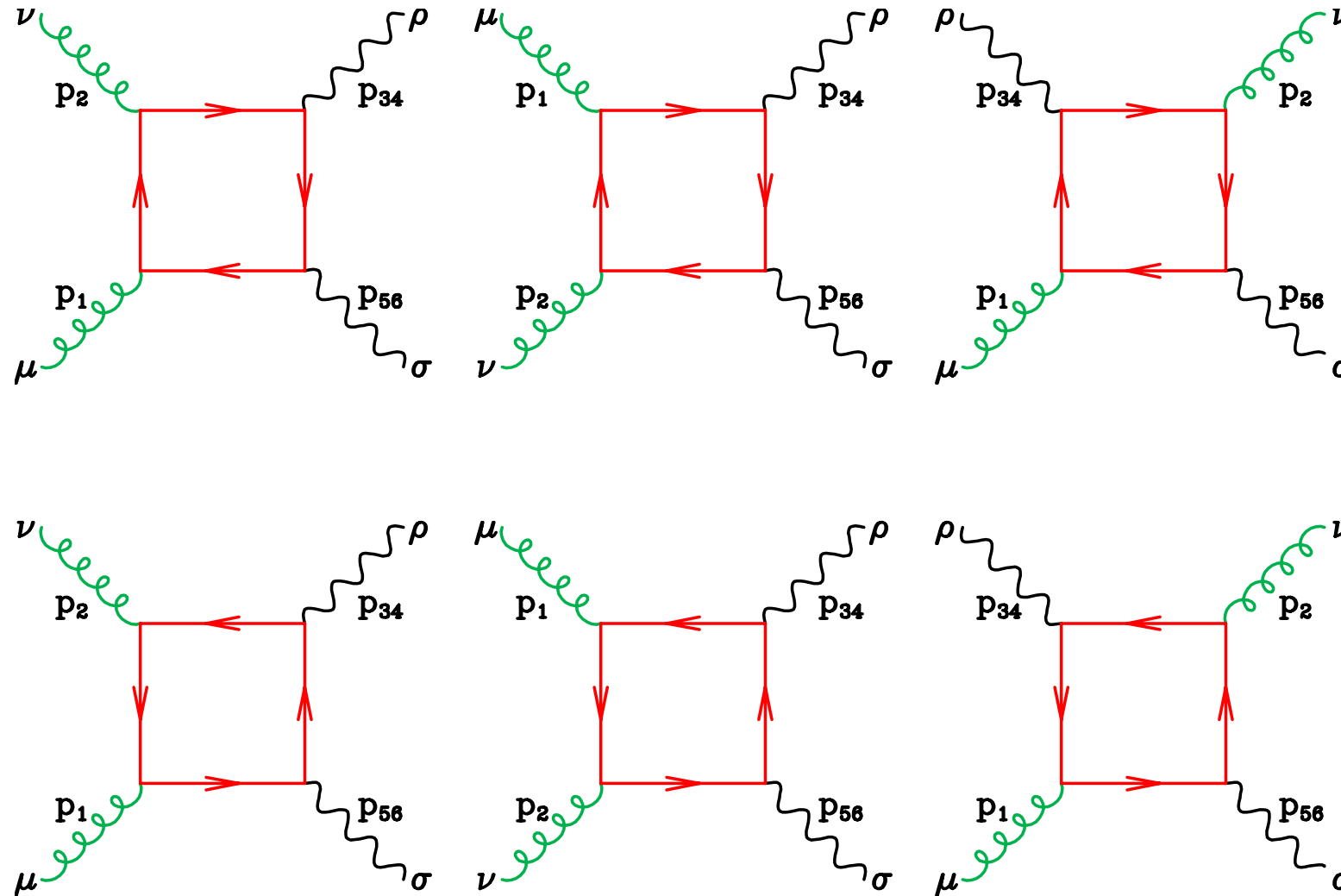
$$-a_2 E^2 + (c_1 - a_1) m_t E$$



$$-(b_1 + c_1) m_t E$$

- First cancellation due to the gauge structure
- Second cancellation requires the Higgs
- c.f Lee, Quigg and Thacker

## Diagrams for $gg \rightarrow Z/g^* + Z/g^*$ (background)



- We perform a stable, analytic calculation of these diagrams and their interference with the Higgs diagrams.
- Obtaining numerical stability is challenging for automatic procedures. Human intervention required.

# Caola-Melnikov method for Higgs width

- Higgs cross section under the peak, section depends on ratio of couplings and width.

$$\sigma_{\text{peak}} \propto \frac{g_i^2 g_f^2}{\Gamma}$$

- Measurements at the peak cannot untangle couplings and width.

- Off-peak cross section is independent of the width, but still depends on  $g_i^2 g_f^2$  (modulo interference, see later).

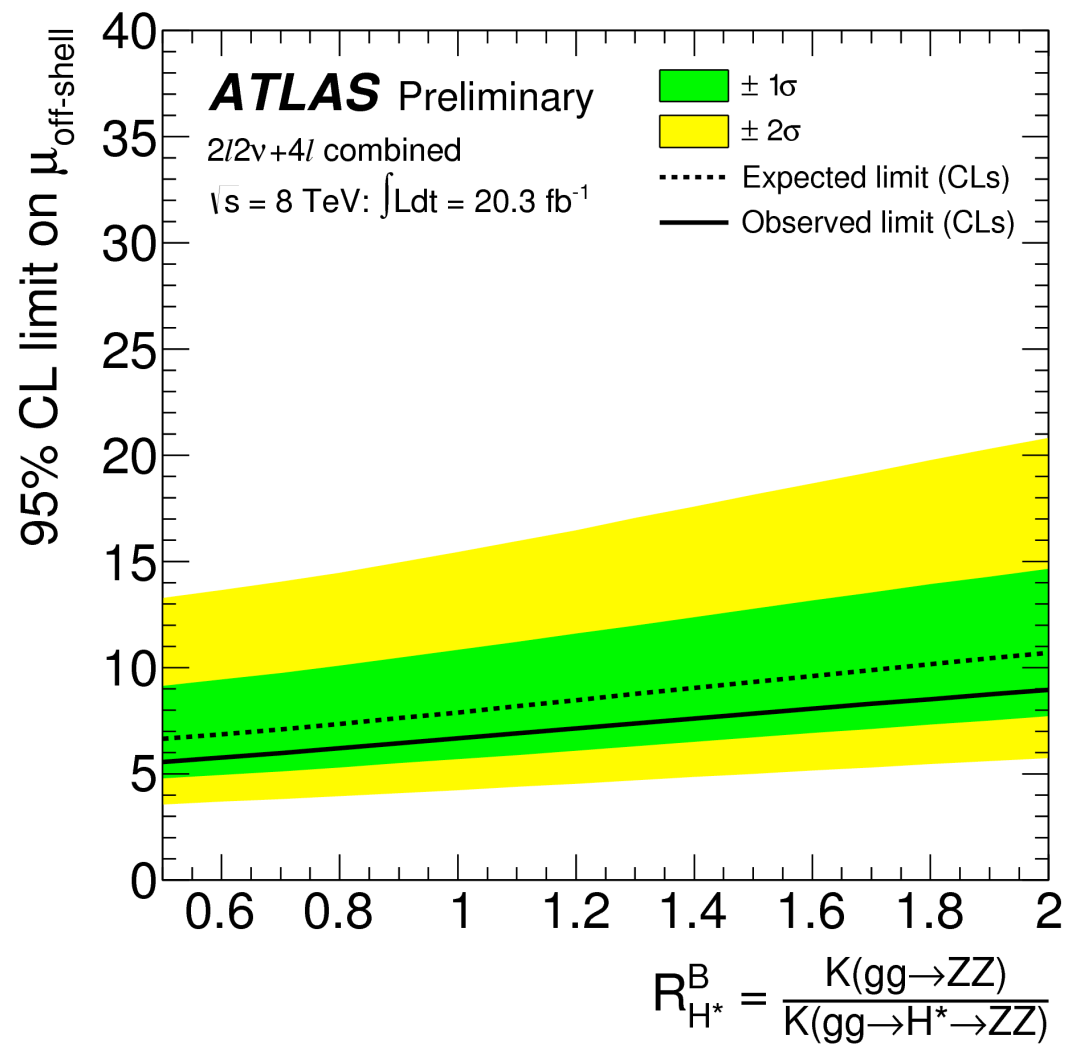
$$\sigma_{\text{off}} \propto g_i^2 g_f^2$$

$$\frac{\left( \frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}} \right)_{\text{experimental gg}}}{\left( \frac{\sigma_{\text{off}}}{\sigma_{\text{peak}}} \right)_{\text{theoretical SM}}} = \frac{\Gamma}{\Gamma_{\text{SM}}}$$

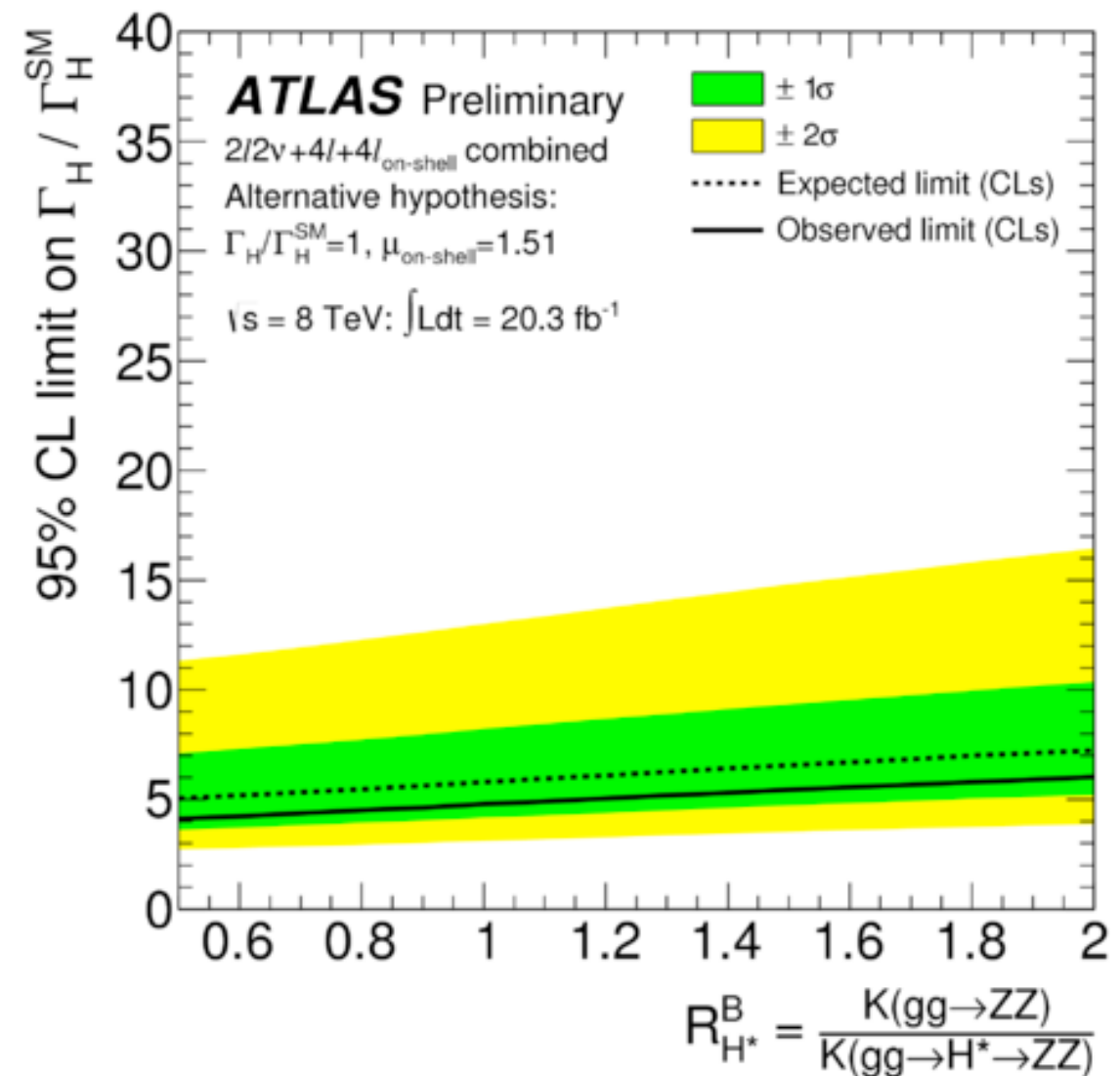
# ATLAS result

ATLAS-CONF-2014-042

- Presented as a function of the unknown relative K factor between “signal” and “background”.



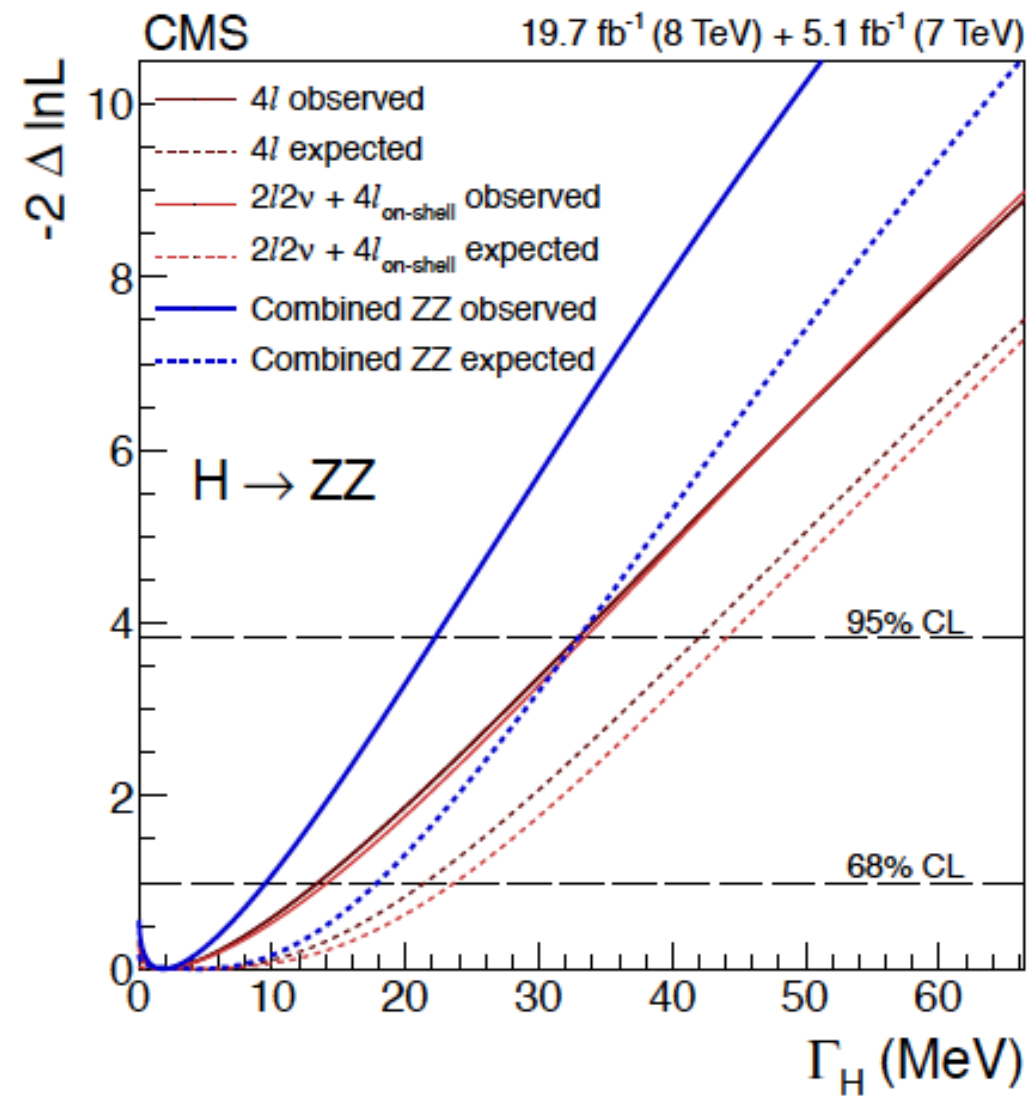
○



# CMS result

arXiv:1405.3455

- $\Gamma_H/\Gamma_H^{\text{SM}}$ :



## Model-dependence of Higgs width bound.

- The bound on the Higgs width holds under the assumption that the coupling constants remain the same over a large span of energy  $\sqrt{s}=126 \rightarrow \sim 500$  GeV.
- If new phenomena are present, this will not always be true.
- In all cases there is great interest in the measurement of the gluon induced 4-lepton cross section away from the Higgs peak.
- If there is a large scale separation between the new phenomena and the off-shellness probed, this can be treated using an effective operator formulation.

$$\mu_{ZZ}^{\text{on}} \equiv \frac{\sigma_h \times \text{BR}(h \rightarrow ZZ \rightarrow 4\ell)}{[\sigma_h \times \text{BR}(h \rightarrow ZZ \rightarrow 4\ell)]_{\text{SM}}} \sim \frac{\kappa_{ggh}^2 \kappa_{hZZ}^2}{\Gamma_h / \Gamma_h^{\text{SM}}},$$
$$\mu_{ZZ}^{\text{off}} \equiv \frac{d\bar{\sigma}_h}{[d\bar{\sigma}_h]_{\text{SM}}} \sim \kappa_{ggh}^2(\hat{s}) \kappa_{hZZ}^2(\hat{s}),$$

Englert and Spannowsky, 1405.0285

Cacciapaglia et al, 1406.1757  
Azatov et al, 1406.6338  
Gaines et al, 1403.4951



# Theoretical predictions for Vector Boson Fusion

# Diagrams for $pp \rightarrow \text{jet} + \text{jet} + e^- e^+ \mu^- \mu^+$

- Off-shell behaviour for VBF subject of much theoretical study.

- Jet cuts

$$p_{T,J} > 30 \text{ GeV}, |\eta_J| < 4.5, R = 0.4$$

- CMS lepton cuts

$$p_{T,\mu} > 5 \text{ GeV}, |\eta_\mu| < 2.4,$$

$$p_{T,e} > 7 \text{ GeV}, |\eta_e| < 2.5,$$

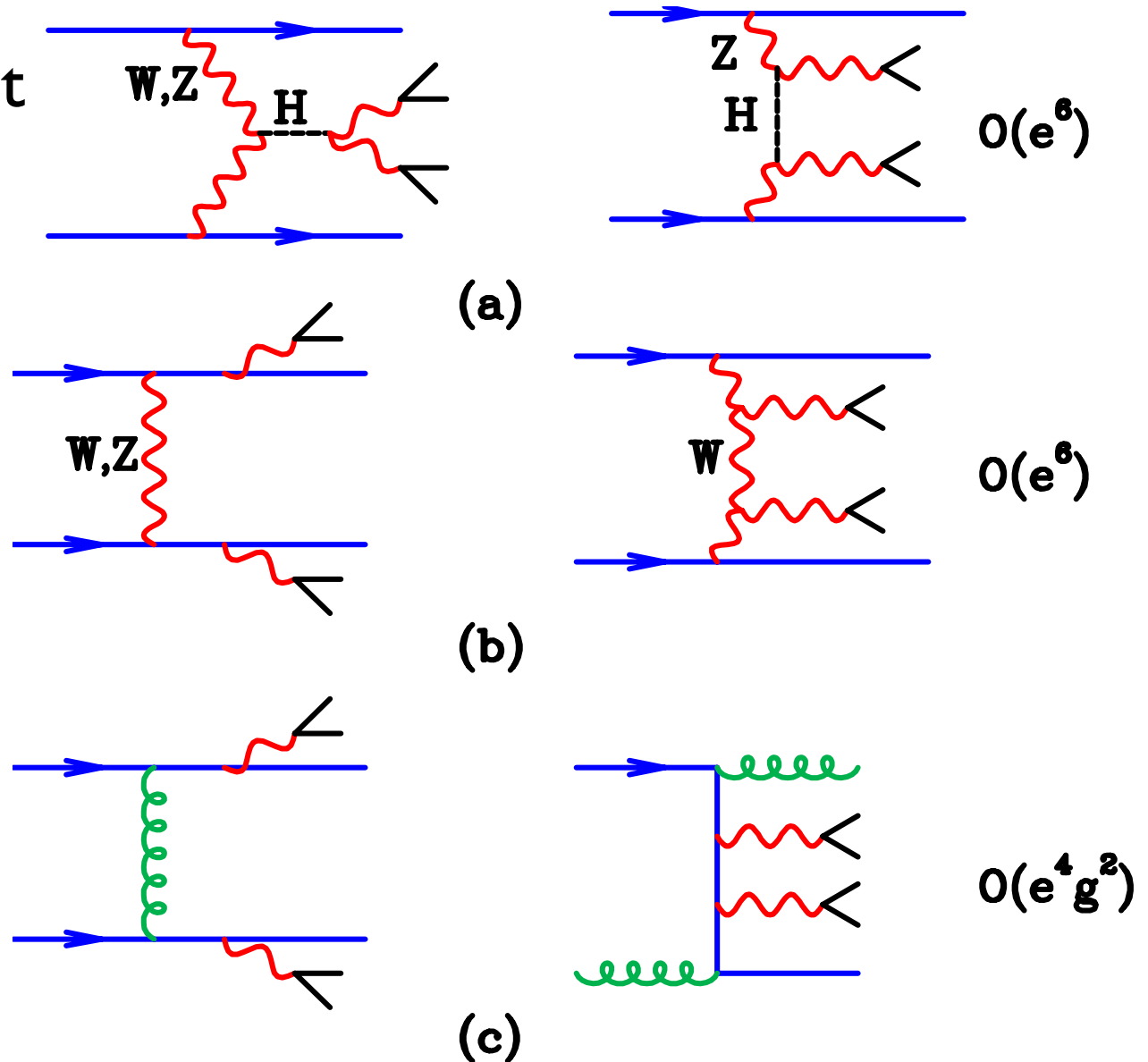
$$m_{ll} > 4 \text{ GeV}, m_{4\ell} > 100 \text{ GeV}.$$

- Additional VBF cuts

$$y_{gap} > 2.4$$

$$\eta_1 \times \eta_2 < 0$$

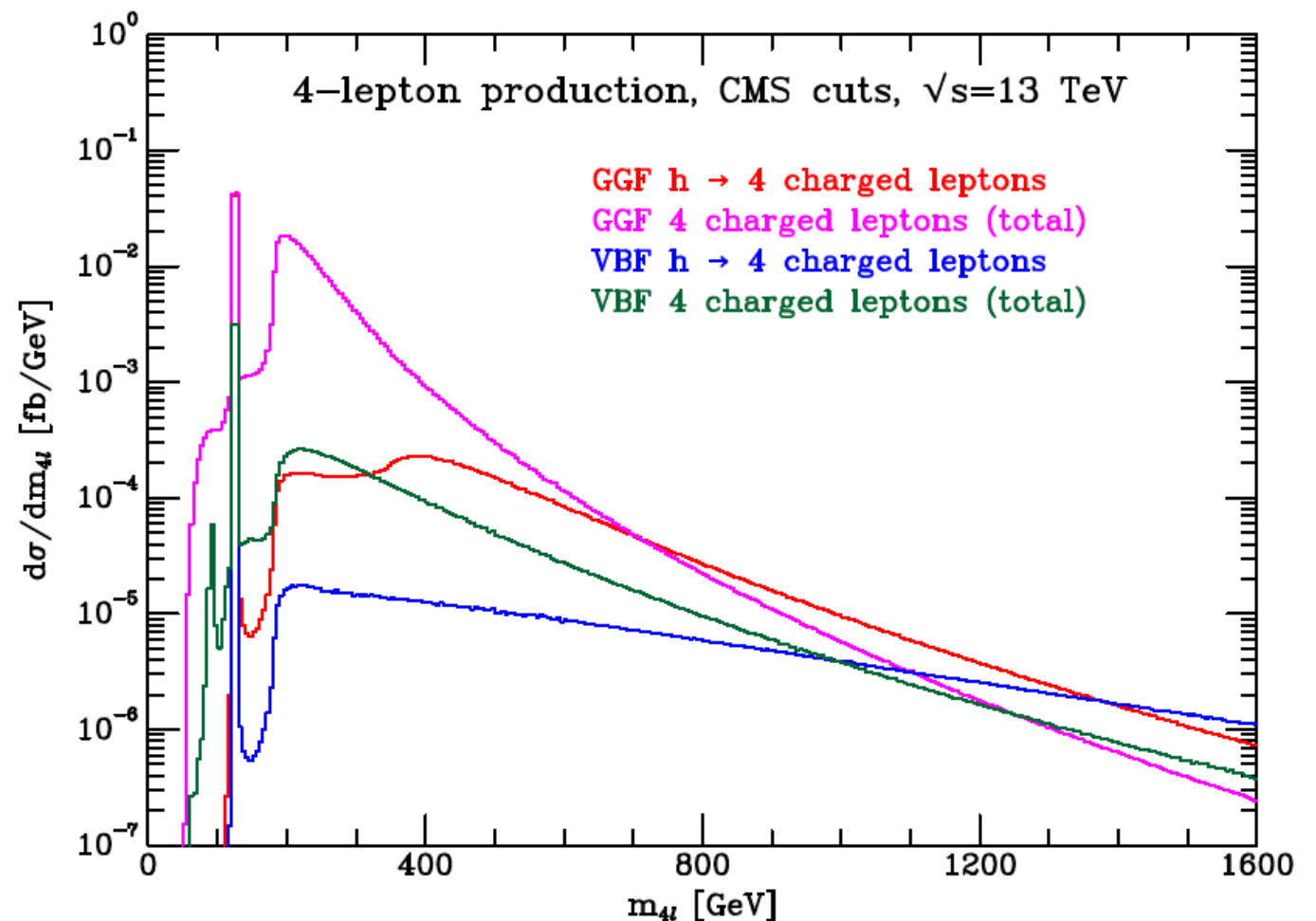
$$m_{j_1 j_2} > 500 \text{ GeV}$$



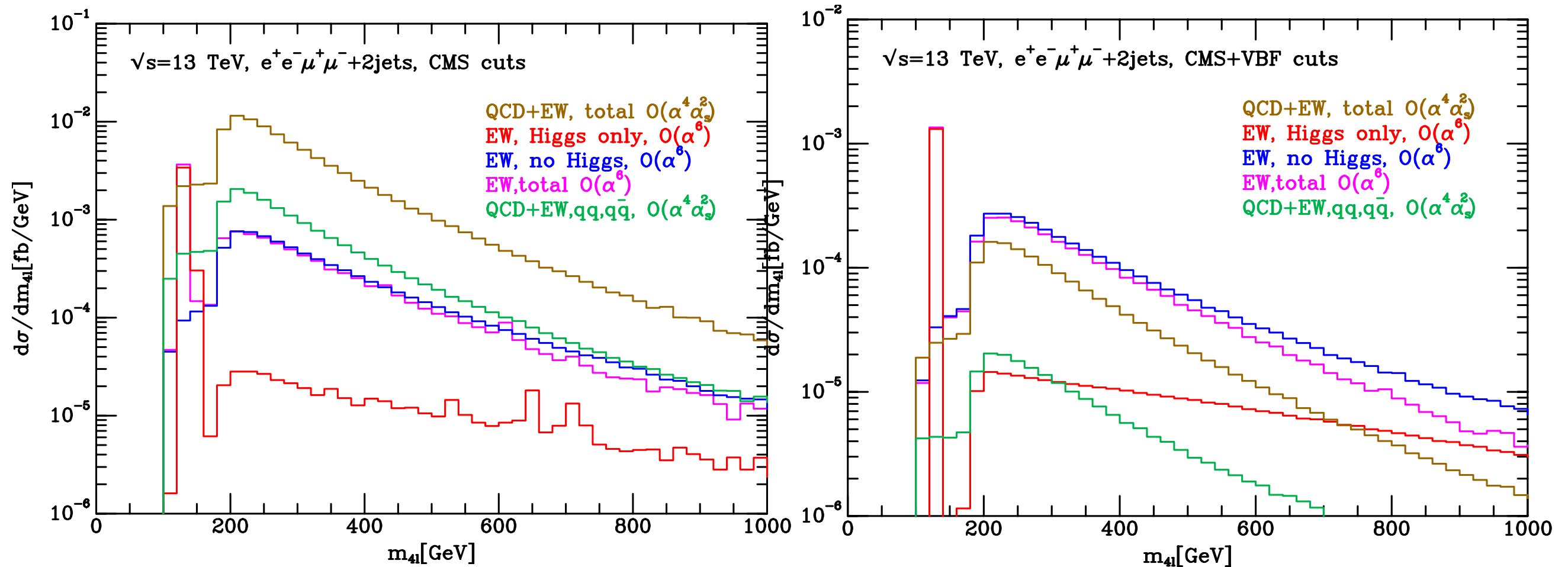
# Gluon-gluon fusion vs Vector boson fusion

- $(pp \rightarrow e^-e^+\mu^-\mu^+) \text{ vs } (pp \rightarrow \text{jet}+\text{jet}+e^-e^+\mu^-\mu^+ \text{ with VBF cuts})$

- EW cross section for Higgs  $\sim 10\%$  of gg fusion (before VBF cuts)
- Higgs tail relatively more important in  $pp \rightarrow \text{jet}+\text{jet}+e^-e^+\mu^-\mu^+$
- Different slope for VBF tail.

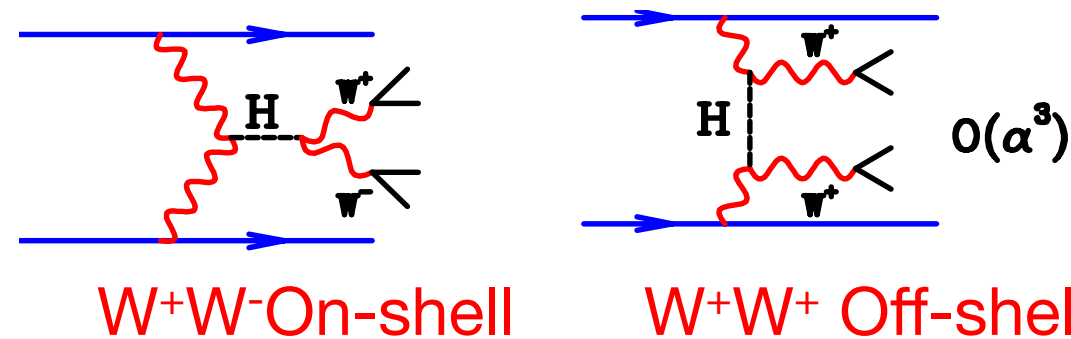


# VBF cuts @ 13 TeV



- Run II will give us access to VBF
- VBF cuts reduce the strong background,  $O(\alpha^4 \alpha_s^2)$ , but  $gq \rightarrow gq e^-e^+\mu^-\mu^+$  still significant.
- This same statement holds for  $W^+W^-, W^\pm Z, ZZ$

Most useful channel is  $W^+W^-$  vs  $W^+W^+$



New idea

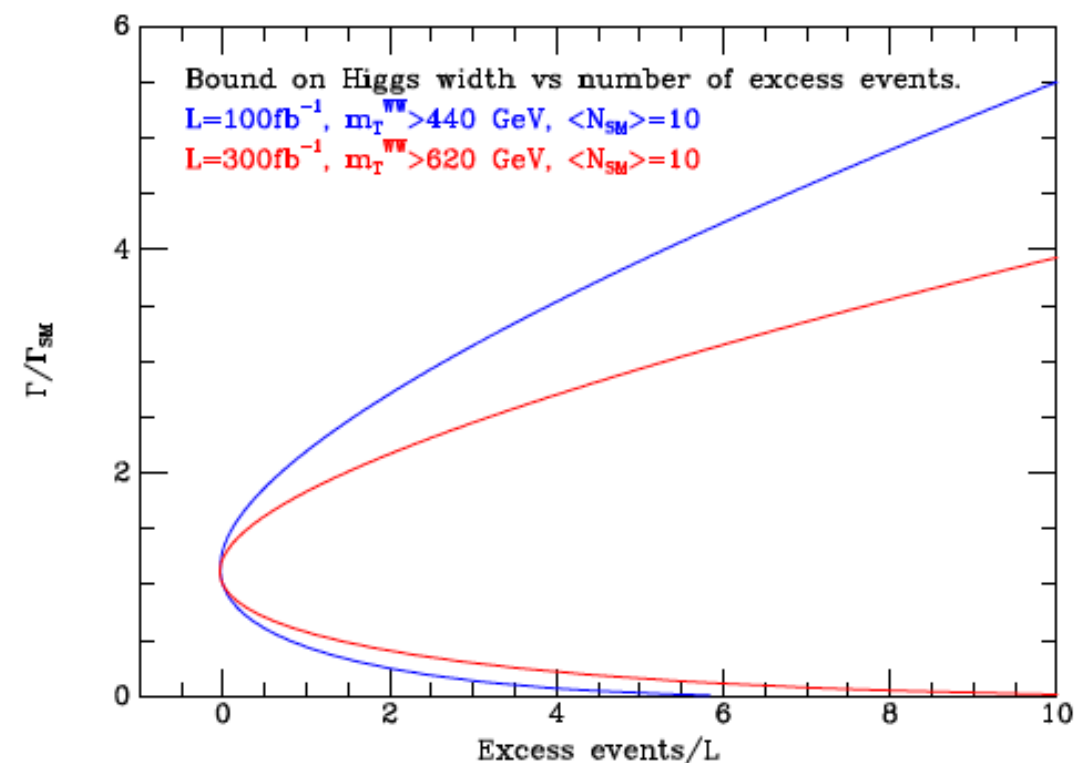
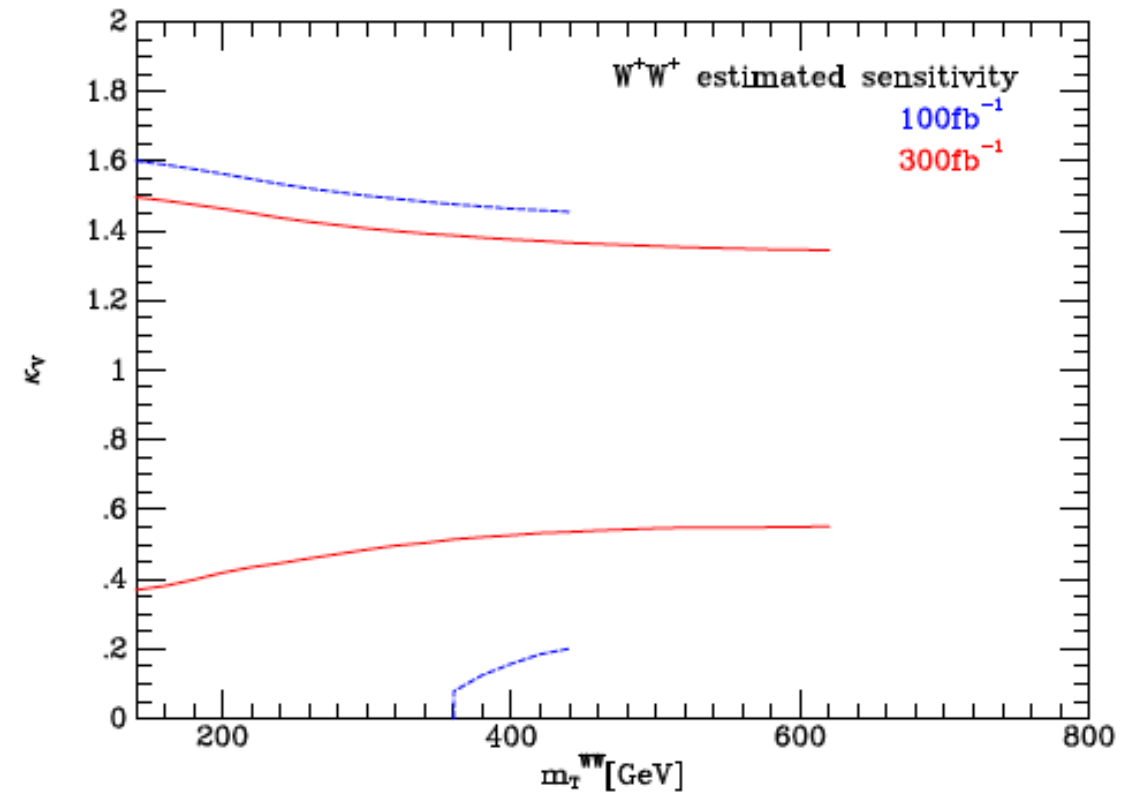
- In the first instance, we work in the effective coupling framework, where standard couplings are rescaled by  $\kappa_V$ .
- At  $\sqrt{s}=8\text{TeV}$ , SM prediction displays a dependence on  $\kappa_V$

$$\sigma_{fiducial}^{same-sign} = 1.015 - 0.106 \kappa_V^2 + 0.040 \kappa_V^4 \text{ fb} .$$

- ATLAS on-shell signal-strength  $\mu_{VBF}^{ATLAS} = 1.27^{+0.53}_{-0.45}$
- ATLAS  $W^+W^+$  measurement  $\sigma^{measured} = 1.3 \pm 0.4(stat) \pm 0.2(syst) \text{ fb} .$
- Bound is  $\kappa_V < 7.8 .$
- current notional width bound  $\Gamma_H < 60.8 \times \Gamma_H^{SM} .$

## Improvement with 100, 300fb<sup>-1</sup> at $\sqrt{s}=13\text{TeV}$

- Expected upper and lower bounds on  $\kappa_V$  obtained from  $W^+W^+$  events as a function of the transverse mass.
- Bounds are cut off when SM prediction falls below 10 events.
- In all cases the best bounds are achieved, taking the highest possible cut on the transverse mass.
- Possible width bounds with (100, 300fb<sup>-1</sup>) are similar to those currently obtained from gg fusion (20fb<sup>-1</sup>).



# Effective coupling dependence of other processes

- $\sqrt{s}=13\text{TeV}$  in  $100\text{fb}^{-1}$
- $M_{(T)} > 300\text{GeV}$
- Note that numbers are not so different for  $\kappa_V=0$  (no Higgs) and  $\kappa_V=1$  (SM)
- For this energy and luminosity we cannot place the cut sufficiently high that the non-cancelling terms dominate.

Signal

$$\left\{ \begin{array}{ll} l^- l^+ \nu \bar{\nu} : & N^{\text{off}} = 127.9 - 42.8 \kappa_V^2 + 20.8 \kappa_V^4 \\ l^+ l^+ \nu \nu : & N^{\text{off}} = 37.2 - 18.3 \kappa_V^2 + 8.3 \kappa_V^4 \\ l^- l^- \bar{\nu} \bar{\nu} : & N^{\text{off}} = 11.0 - 4.1 \kappa_V^2 + 1.8 \kappa_V^4 \\ l^+ l^- l^+ \nu : & N^{\text{off}} = 23.5 - 6.8 \kappa_V^2 + 3.2 \kappa_V^4 \\ l^+ l^- l^- \bar{\nu} : & N^{\text{off}} = 11.3 - 3.3 \kappa_V^2 + 1.6 \kappa_V^4 \\ l^- l^+ l^- l^+ : & N^{\text{off}} = 6.0 - 3.0 \kappa_V^2 + 1.5 \kappa_V^4 \end{array} \right.$$

Signal +  
Background

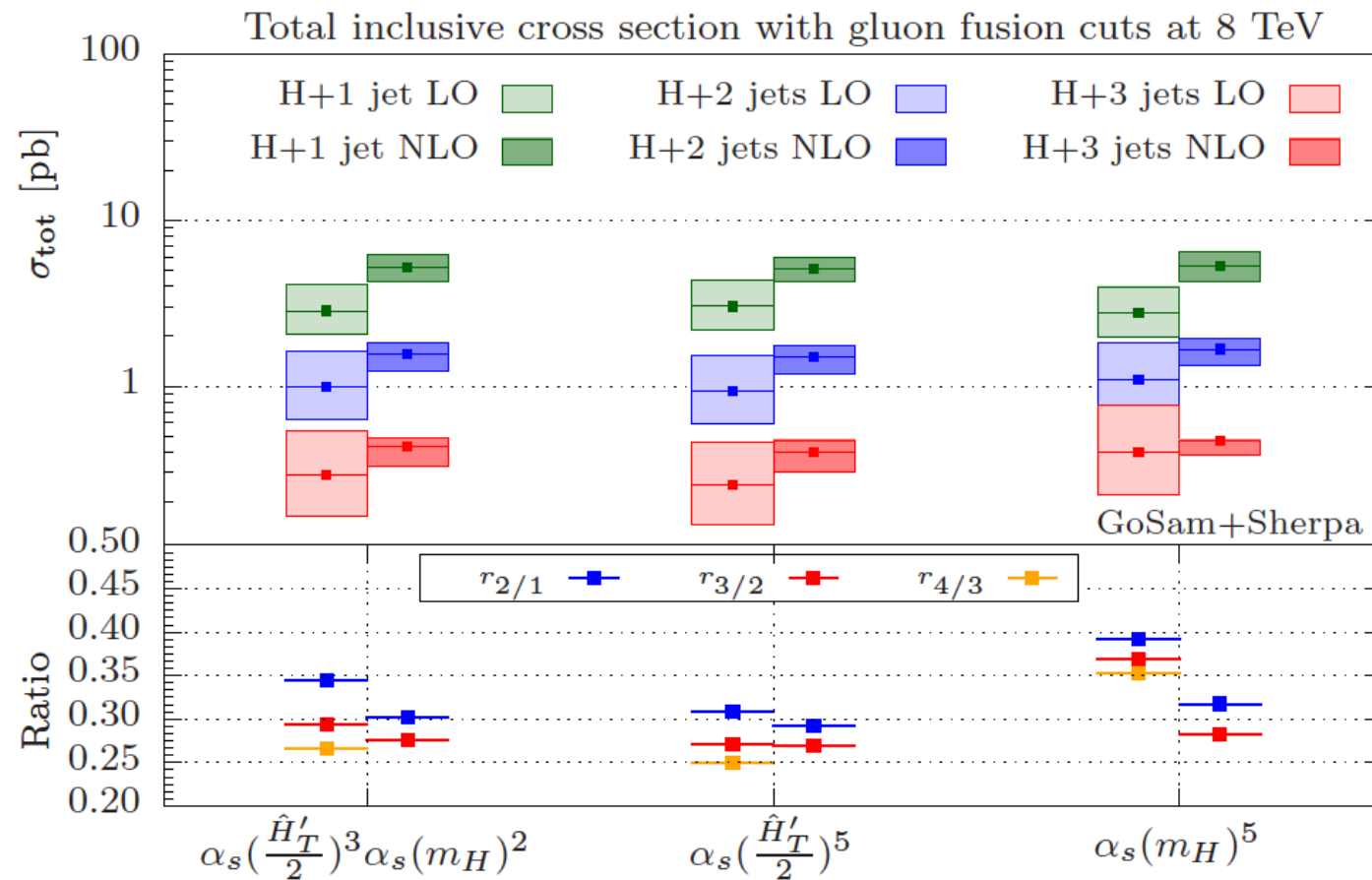
$$\left\{ \begin{array}{ll} l^- l^+ \nu \bar{\nu} : & N^{\text{off}} = 224.8 - 42.8 \kappa_V^2 + 20.8 \kappa_V^4 \\ l^+ l^+ \nu \nu : & N^{\text{off}} = 38.8 - 18.3 \kappa_V^2 + 8.3 \kappa_V^4 \\ l^- l^- \bar{\nu} \bar{\nu} : & N^{\text{off}} = 11.5 - 4.1 \kappa_V^2 + 1.8 \kappa_V^4 \\ l^+ l^- l^+ \nu : & N^{\text{off}} = 60.1 - 6.8 \kappa_V^2 + 3.2 \kappa_V^4 \\ l^+ l^- l^- \bar{\nu} : & N^{\text{off}} = 29.5 - 3.3 \kappa_V^2 + 1.6 \kappa_V^4 \\ l^- l^+ l^- l^+ : & N^{\text{off}} = 9.0 - 3.0 \kappa_V^2 + 1.5 \kappa_V^4 \end{array} \right.$$

# Perturbative QCD 2015 and onwards

- The most significant result of Run I of the LHC is the discovery of the Higgs boson in 2012
- Higgs boson (produced predominantly by gluon fusion) radiates copiously, thus emphasizing the importance of radiative corrections.
- e.g. for Higgs total cross section  $\sigma = 12.937 \times (1 + 1.28 + 0.77)$ .
- Perturbative QCD is front and centre in the physics program of run II.
- “With data taken in coming years at or near to the design energy of 14 TeV, a broader picture of physics at the TeV scale will emerge with implications for the future of the energy frontier program. Amongst the essential inputs will be precision measurements of the properties of the Higgs boson and direct searches for new physics that will make significant inroads into new territory.” [ATLAS Physics at High Luminosity, 1307.7292](#)

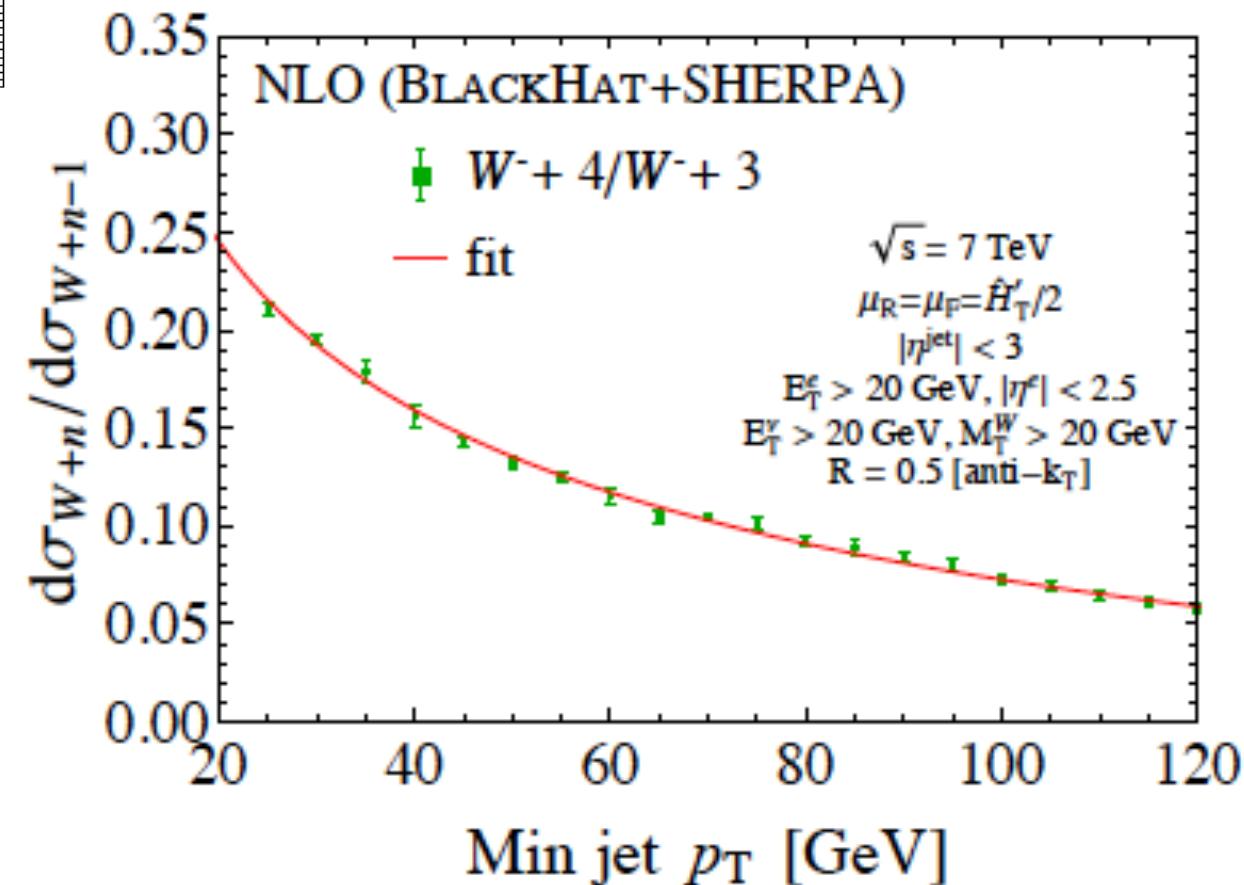


# Propensity to radiate



Greiner

“Berends-Giele” ratio greater for Higgs than for W



# The next frontier: NNLO

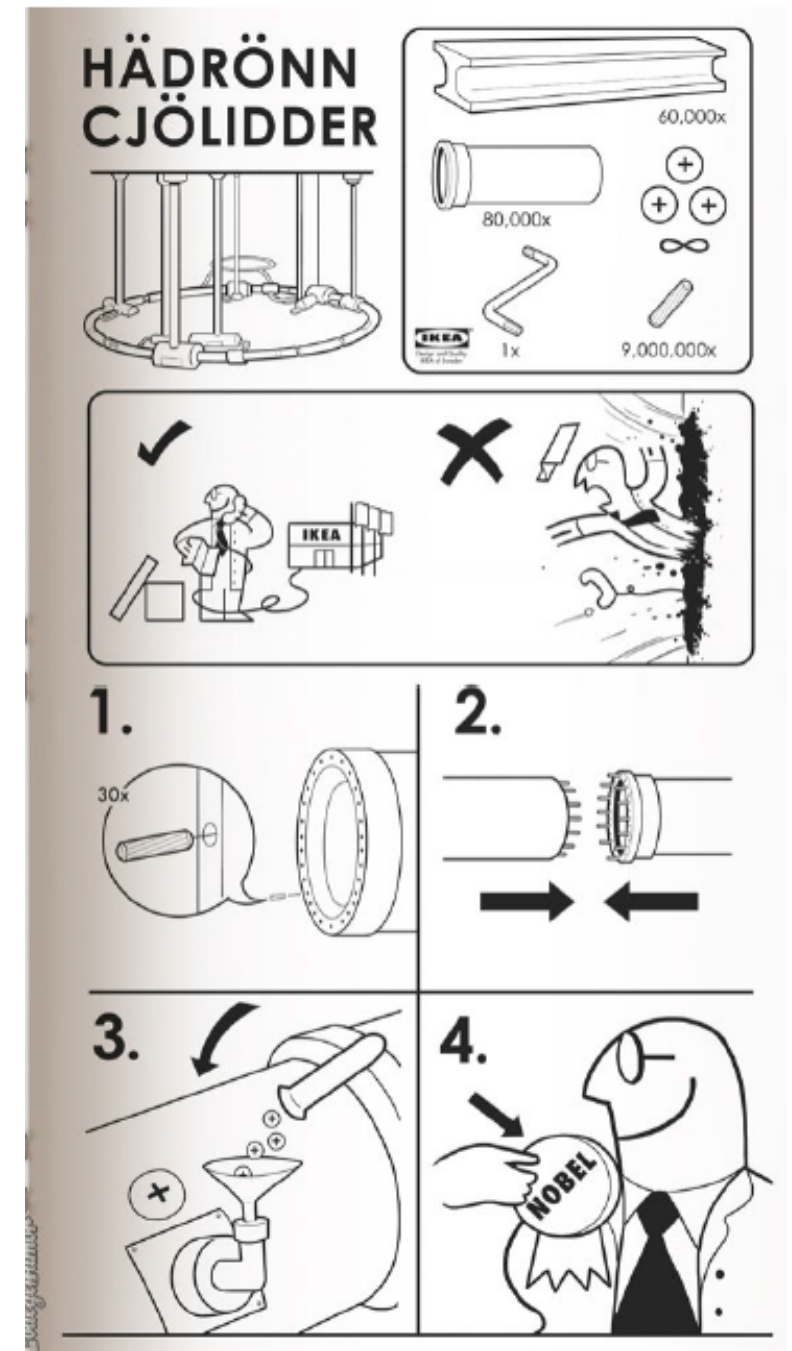
- NNLO calculations roughly at the level of NLO in 1990.
  - NLO 2 to 2 virtual matrix elements known
  - NLO top cross section (total and differential) known
  - NLO 2 to 3 calculations just beginning to be tackled?
- NLO calculations complete ~2010
- Will we make faster progress on NNLO?

## NNLO - 2 loop matrix elements

- Tremendous advance in analytical methods
- differential equations, canonical basis of integrals,....
- $2 \rightarrow 2$  processes with four independent scales seem to be within reach, but extension to  $2 \rightarrow 3$  processes, eg  $gg \rightarrow V_1 V_2 g$  seem currently out of reach.
- If  $2 \rightarrow 3$  represents a wall, then we need to investigate other methods.
- The investment in numerical methods compared to analytic methods, seems to me to be too small.
  - Contour deformation in FP space, sector decomposition Schlenk
  - Contour deformation in momentum space, e.g. Becker, Weinzierl  
1211.0509

# NNLO-some assembly required

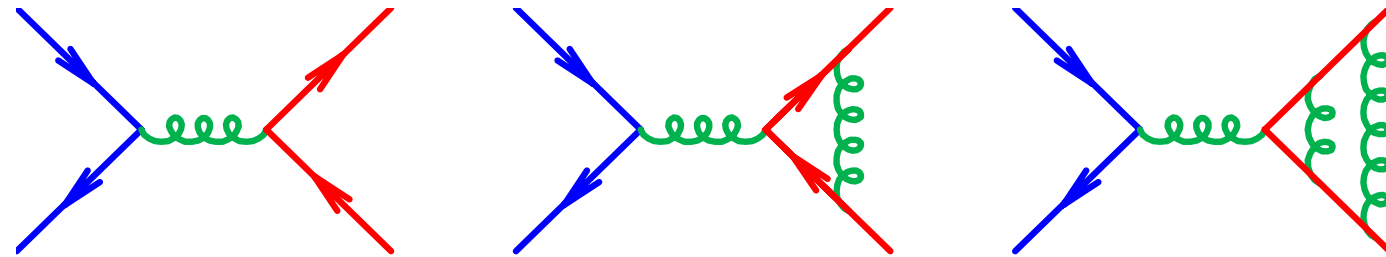
- Contributions from Real-Real, Real-Virtual and Virtual-Virtual.
- For the lower multiplicities the poles are explicit, whereas as for higher multiplicities, they appear after integration.
- Thus the requirement to cancel the poles appears to be in contradiction with the desire for a differential cross section.



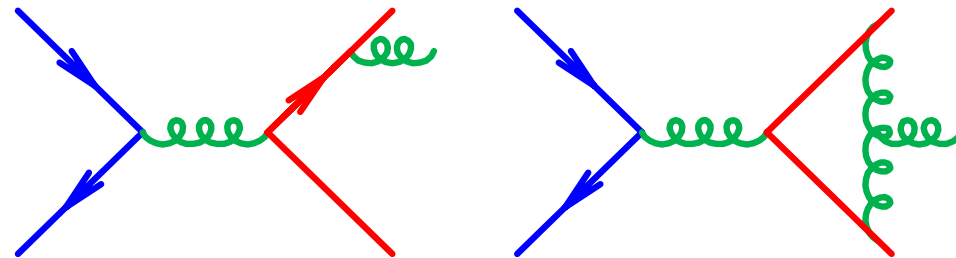
# NNLO diagrams

- Challenge is not the calculation of the individual diagrams, but rather the assembly of pieces that individually contain infrared divergences

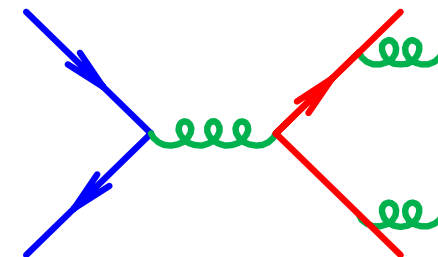
examples of  $2 \rightarrow 2$   
diagrams: VV



examples of  $2 \rightarrow 3$   
diagrams: RV



examples of  $2 \rightarrow 4$   
diagram: RR



- In different regions of phase space, different subsets of partons lead to singularities of the matrix elements.

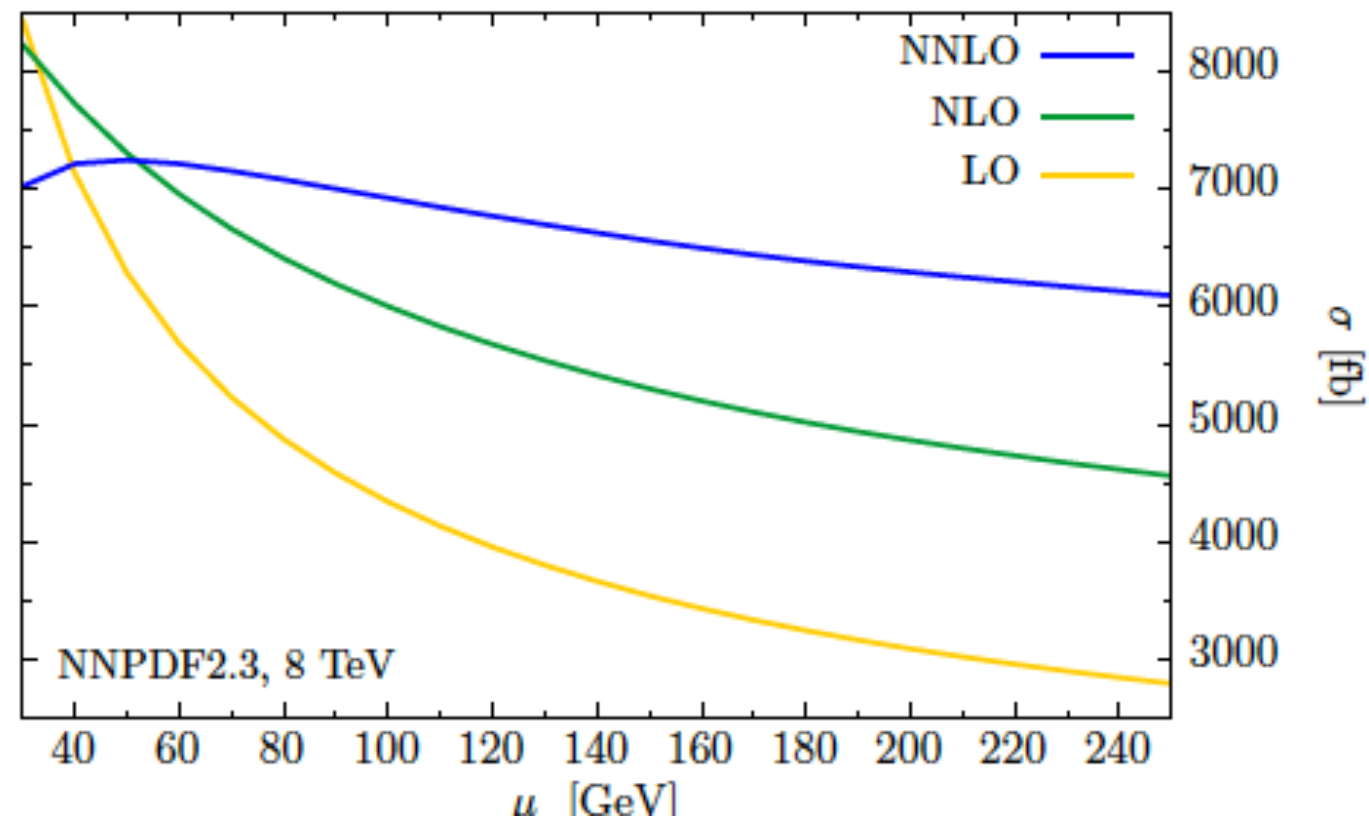
# NNLO - Four main combination methods

- Antenna
  - Pros: Analytic cancellation of poles, demonstrated for 2- $\rightarrow$ 2 colored scattering
  - Con: More challenging interface to existing NLO codes
- Sector improved residue subtraction scheme.
  - Pros: Brute force method, offers possibility of generalization to arbitrary processes, demonstrated for 2- $\rightarrow$ 2 colored scattering
  - Con: Numerical cancellation of poles
- qt/N-jettiness subtraction
  - Pro: Meshes well with existing NLO codes
  - Con: Slicing method, have to demonstrate independence from cutoff parameter.
- Colour subtraction
  - Pro: Local subtraction terms
  - Con: No NNLO application to processes with initial state hadrons yet.

# Higgs+1 jet

Boughezal et al, 1504.07922, 1505.03893  
Caola et al, 1508.02684

- $\sigma = 17.5 + 1.1 - 1.4 \text{ pb}$
- QCD corrections depend on the kinematics, (K-factor dependent on  $p_T$  cut)
- Also results for pure glue from [Chen et al, 1408.5325](#)
- We look forward to a detailed comparison of the two (three) results



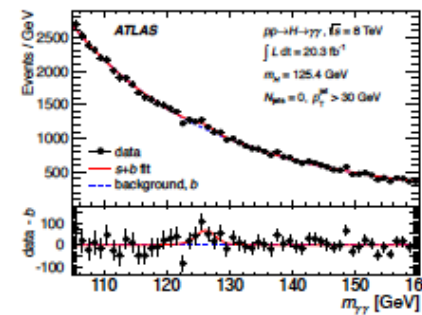
## At 13 TeV in effective theory

Process	$\alpha_s^2$	$\alpha_s^3$	$\alpha_s^4$	$\alpha_s^5$
$\sigma(pp \rightarrow H)$ pb [1]	13	30	40	43
$\sigma(pp \rightarrow H + \text{jet})$ pb[2]		10	15	18
$\sigma(pp \rightarrow H + 2 \text{ jet})$ pb[3]			3.5	5.1
$\sigma(pp \rightarrow H + 3 \text{ jet})$ pb[3]				1.6

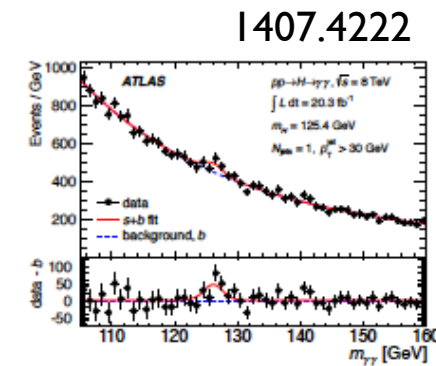
+  $O(\alpha_s^6)$  results  
from [Greiner](#) here

# Higgs + 1 jet, (fiducial cross section)

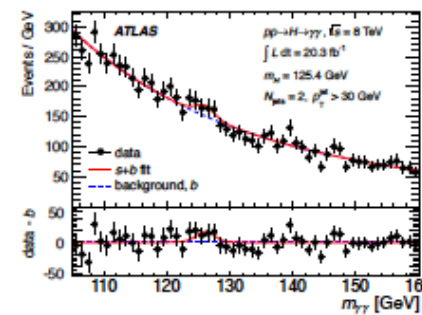
- ATLAS has published Higgs cross section separated by the number of jets, in their fiducial region.
- Allow comparison of their results with new NNLO results (Caola et al, 1508.02684) in their fiducial region.



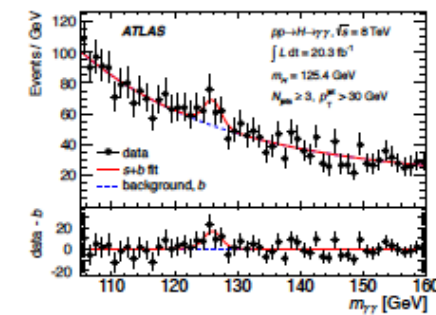
(a)



(b)



(c)



(d)

ATLAS:  $\sigma_{H+j}^{\text{fid}}(8 \text{ TeV}) = 21.5 \pm 5.3(\text{stat.}) \pm_{2.2}^{2.4}(\text{syst.}) \pm 0.6(\text{lumi}) \text{ fb.}$

Fixed order:  $\sigma_{\text{LO}}^{\text{fid}} = 5.43_{-1.49}^{+2.32} \text{ fb}, \quad \sigma_{\text{NLO}}^{\text{fid}} = 7.98_{-1.46}^{+1.76} \text{ fb}, \quad \sigma_{\text{NNLO}}^{\text{fid}} = 9.45_{-0.82}^{+0.58} \text{ fb},$

- ATLAS result larger by a factor of 2.1-2.5, (2.4  $\sigma$  effect)

Compare and contrast

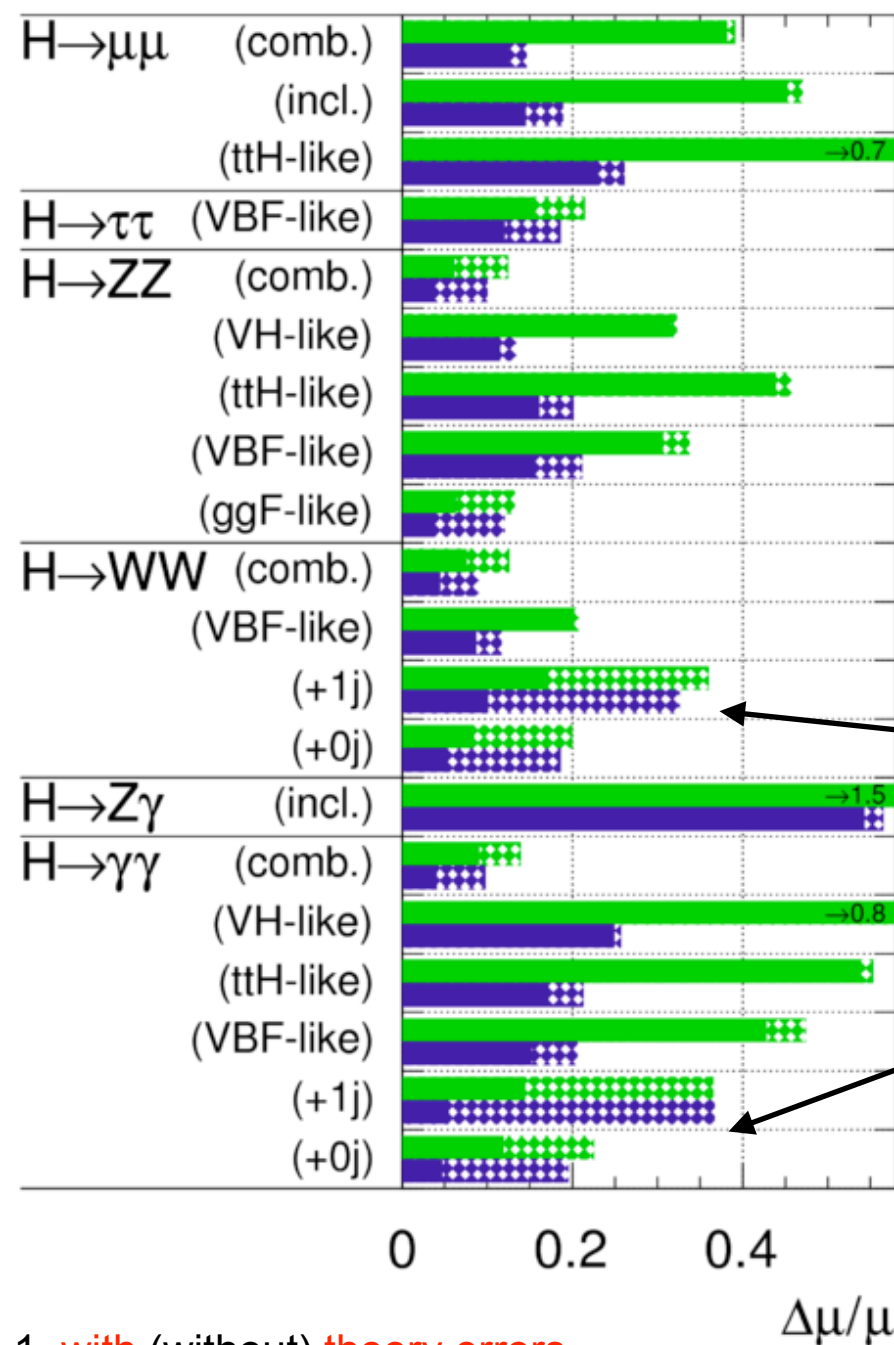


# Influence of theory on signal strengths

ATL-PHYS-PUB-2013-014

**ATLAS** Simulation Preliminary

$\sqrt{s} = 14 \text{ TeV}$ :  $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$  ;  $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



Already impact here

ATLAS: Syst. errors as run 1, with (without) theory errors

# NNLO:Wish-listeria I

A judicious combination of the desirable and the possible?

Process	State of the Art	Desired	Delivered
H	$d\sigma$ @ NNLO QCD (expansion in $1/m_t$ ) full $m_t/m_b$ dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \rightarrow \infty$ limit	$d\sigma$ @ NNNLO QCD (infinite- $m_t$ limit) full $m_t/m_b$ dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects	1503.06056[2]  1309.0017[3], 1501.04637[4] 1407.3773[5]
H + j	$d\sigma$ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	$d\sigma$ @ NNLO QCD (infinite- $m_t$ limit) and finite-quark-mass effects @ NLO QCD and NLO EW	1408.5325[6], 1504.07922[7], 1505.03893[8]
H + 2j	$\sigma_{\text{tot}}(\text{VBF})$ @ NNLO(DIS) QCD $d\sigma(\text{VBF})$ @ NLO EW $d\sigma(\text{gg})$ @ NLO QCD (infinite- $m_t$ limit) and finite-quark-mass effects @ LO QCD	$d\sigma(\text{VBF})$ @ NNLO QCD + NLO EW  $d\sigma(\text{gg})$ @ NNLO QCD (infinite- $m_t$ limit) and finite-quark-mass effects @ NLO QCD and NLO EW	1506.02660[9]
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW $\sigma_{\text{tot}}(\text{gg})$ @ NLO QCD (infinite- $m_t$ limit)	with $H \rightarrow b\bar{b}$ @ same accuracy $d\sigma(\text{gg})$ @ NLO QCD with full $m_t/m_b$ dependence	1501.07226[10]
tH and $\bar{t}H$	$d\sigma(\text{stable top})$ @ LO QCD	$d\sigma(\text{top decays})$ @ NLO QCD and NLO EW	
t $\bar{t}H$	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD and NLO EW	1407.0823[11]
gg $\rightarrow$ HH	$d\sigma$ @ NLO QCD (leading $m_t$ dependence) $d\sigma$ @ NNLO QCD (infinite- $m_t$ limit)	$d\sigma$ @ NLO QCD with full $m_t/m_b$ dependence	1408.2422[12, 13]

## Wish-listeria II

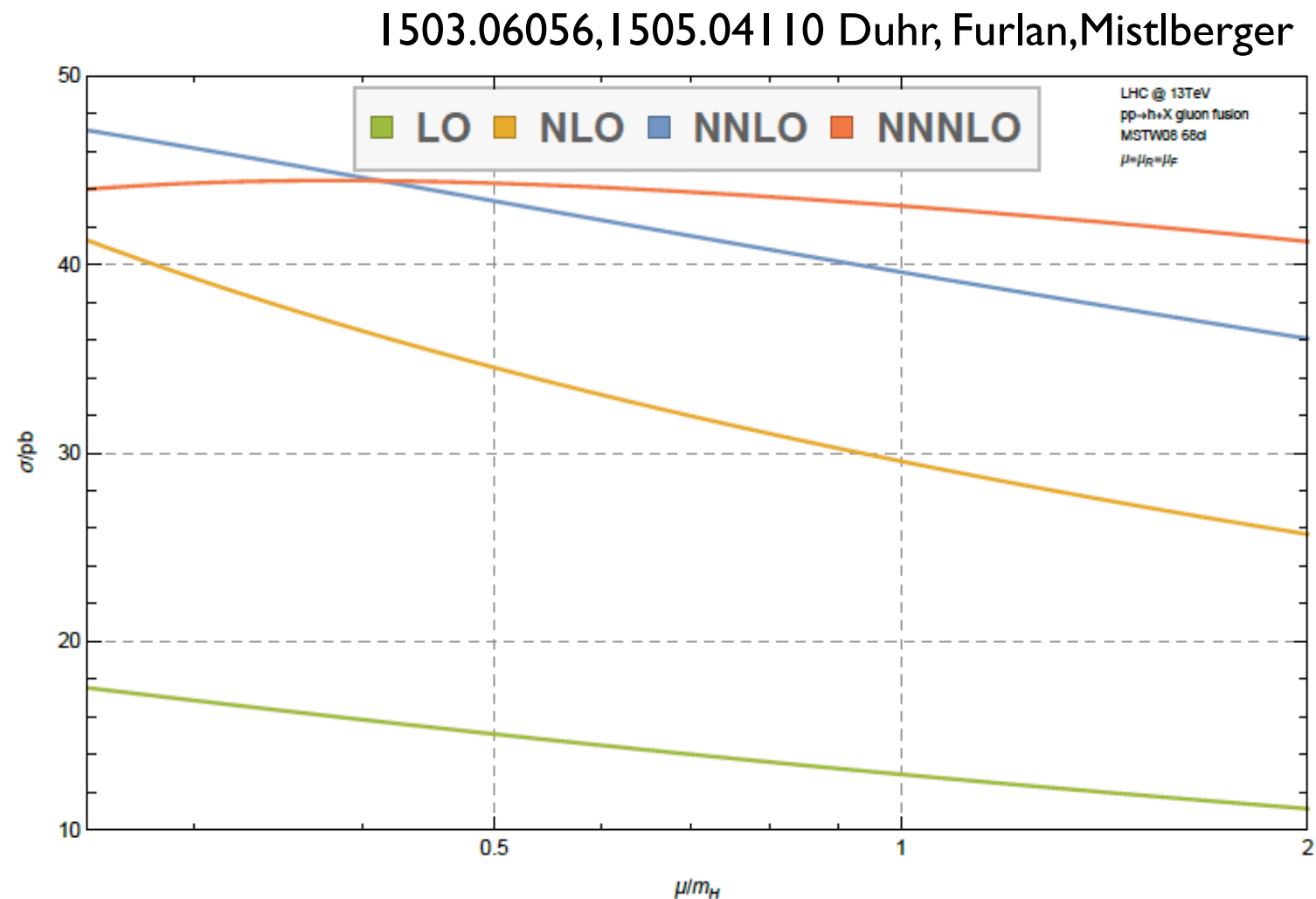
Process	State of the Art	Desired	Delivered
$t\bar{t}$	$\sigma_{\text{tot}}(\text{stable tops})$ @ NNLO QCD $d\sigma(\text{top decays})$ @ NLO QCD $d\sigma(\text{stable tops})$ @ NLO EW	$d\sigma(\text{top decays})$ @ NNLO QCD + NLO EW	1411.3007[15]
$t\bar{t} + j(j)$	$d\sigma(\text{NWA top decays})$ @ NLO QCD	$d\sigma(\text{NWA top decays})$ @ NNLO QCD + NLO EW	
$t\bar{t} + Z$	$d\sigma(\text{stable tops})$ @ NLO QCD	$d\sigma(\text{top decays})$ @ NLO QCD + NLO EW	
single-top	$d\sigma(\text{NWA top decays})$ @ NLO QCD	$d\sigma(\text{NWA top decays})$ @ NNLO QCD + NLO EW	1404.7116[16]
dijet	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW (weak)	$d\sigma$ @ NNLO QCD + NLO EW	1412.3427[17], 15xx.xxxx
3j	$d\sigma$ @ NLO QCD	$d\sigma$ @ NNLO QCD + NLO EW	
$\gamma + j$	$d\sigma$ @ NLO QCD $d\sigma$ @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	

# Wish-listeria III

Process	State of the Art	Desired	Delivered
V	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay}) @ \text{NNNLO QCD}$ and $@ \text{NNLO QCD+EW}$ NNLO+PS	1407.2940[18]
V + j(j)	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ $d\sigma(\text{lept. V decay}) @ \text{NLO EW}$	$d\sigma(\text{lept. V decay})$ $@ \text{NNLO QCD} + \text{NLO EW}$	1504.02131[10]
VV'	$d\sigma(\text{V decays}) @ \text{NLO QCD}$ $d\sigma(\text{on-shell V decays}) @ \text{NLO EW}$	$d\sigma(\text{decaying off-shell V})$ $@ \text{NNLO QCD} + \text{NLO EW}$	1309.7000[19], 1405.2219[20], 1408.5243[21], 1504.01330[22]
gg $\rightarrow$ VV	$d\sigma(\text{V decays}) @ \text{LO QCD}$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	
V $\gamma$	$d\sigma(\text{V decay}) @ \text{NLO QCD}$ $d\sigma(\text{PA, V decay}) @ \text{NLO EW}$	$d\sigma(\text{V decay})$ $@ \text{NNLO QCD} + \text{NLO EW}$	
Vb $\bar{b}$	$d\sigma(\text{lept. V decay}) @ \text{NLO QCD}$ massive b	$d\sigma(\text{lept. V decay}) @ \text{NNLO QCD}$ + NLO EW, massless b	
VV' $\gamma$	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays})$ $@ \text{NLO QCD} + \text{NLO EW}$	
VV'V''	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays})$ $@ \text{NLO QCD} + \text{NLO EW}$	
VV' + j	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays})$ $@ \text{NLO QCD} + \text{NLO EW}$	
VV' + jj	$d\sigma(\text{V decays}) @ \text{NLO QCD}$	$d\sigma(\text{V decays})$ $@ \text{NLO QCD} + \text{NLO EW}$	
$\gamma\gamma$	$d\sigma @ \text{NNLO QCD} + \text{NLO EW}$	$q_T$ resummation at NNLL matched to NNLO	1505.03162[23]

Considerable amount of red ink since mid 2014!

# Beyond N<sup>2</sup>LO: Higgs total cross section at N<sup>3</sup>LO

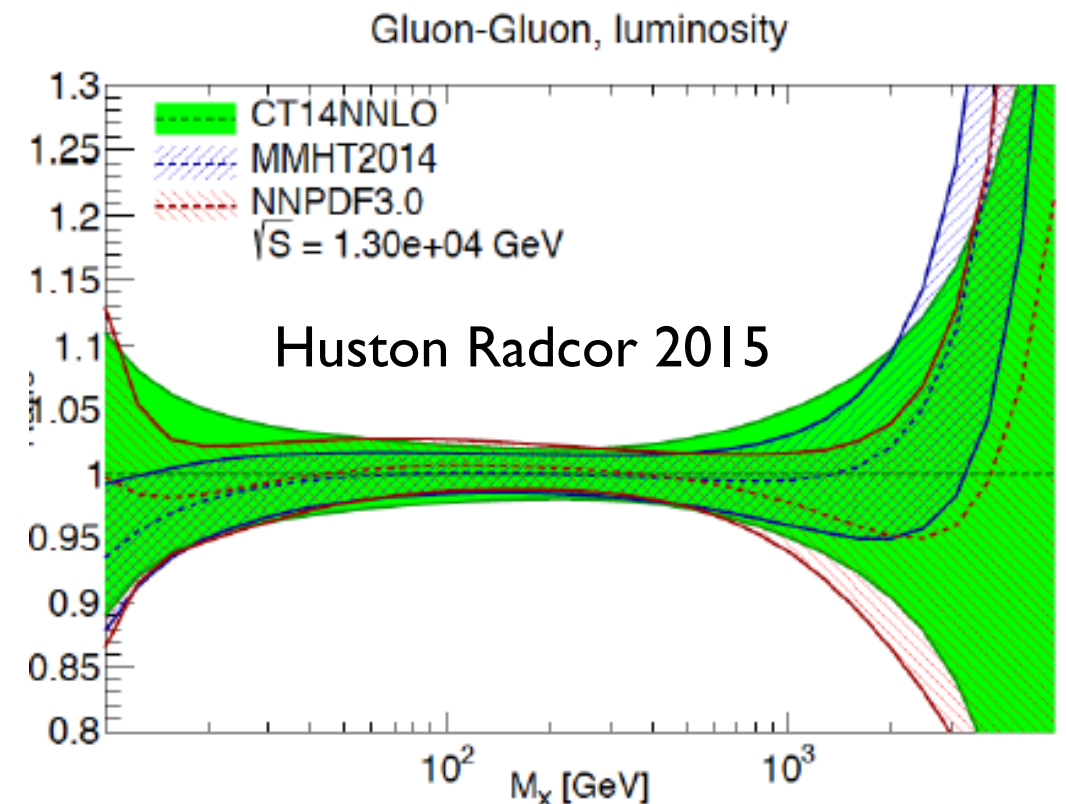


- $\sigma = 44.31^{+0.31\%}_{-2.64\%} \text{ pb}$  for  $\mu \in [m_H/4, m_H]$  at N<sup>3</sup>LO
- At N<sup>2</sup>LO this uncertainty is  $\pm 9\%$



# Uncertainty budget for $gg \rightarrow H$

- According to Anastasiou et al, after the  $N^3LO$  calculation the dominant uncertainty is the PDF and  $\alpha_s$ .
- However recent progress in PDF fits has reduced the uncertainty so that it is also at the 2% level.
- Most studies of the evolution of the uncertainty in the gluon distribution are targeted at larger  $x$ .



NNPDF down by 2-2.5%, CT14 up by ~1%,  
MMHT14 down by ~0.5%

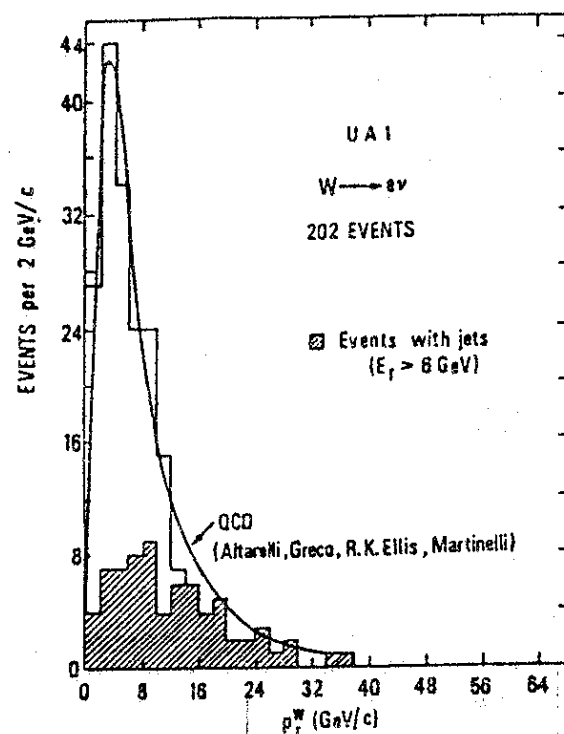
partially data, partially corrections in  
fitting code, partially changes  
in fitting procedures

	CT14	MMHT2014	NNPDF3.0
scale = $m_H$			
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

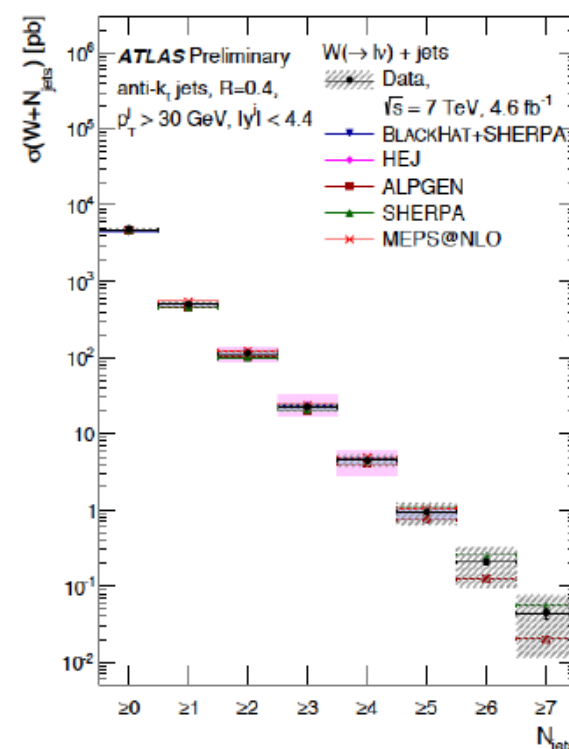
The PDF uncertainty using this new generation of PDFs will be similar in size to the NNLO scale uncertainty and to the  $\alpha_s(m_Z)$  uncertainty.

# Summary

- It is a great time to work on radiative corrections. Higgs is a central theme of run II at the LHC; it radiates copiously.
- Perturbative QCD can improve the interpretation of LHC experiments. Fermilab would do well to continue to invest in this field.



1984

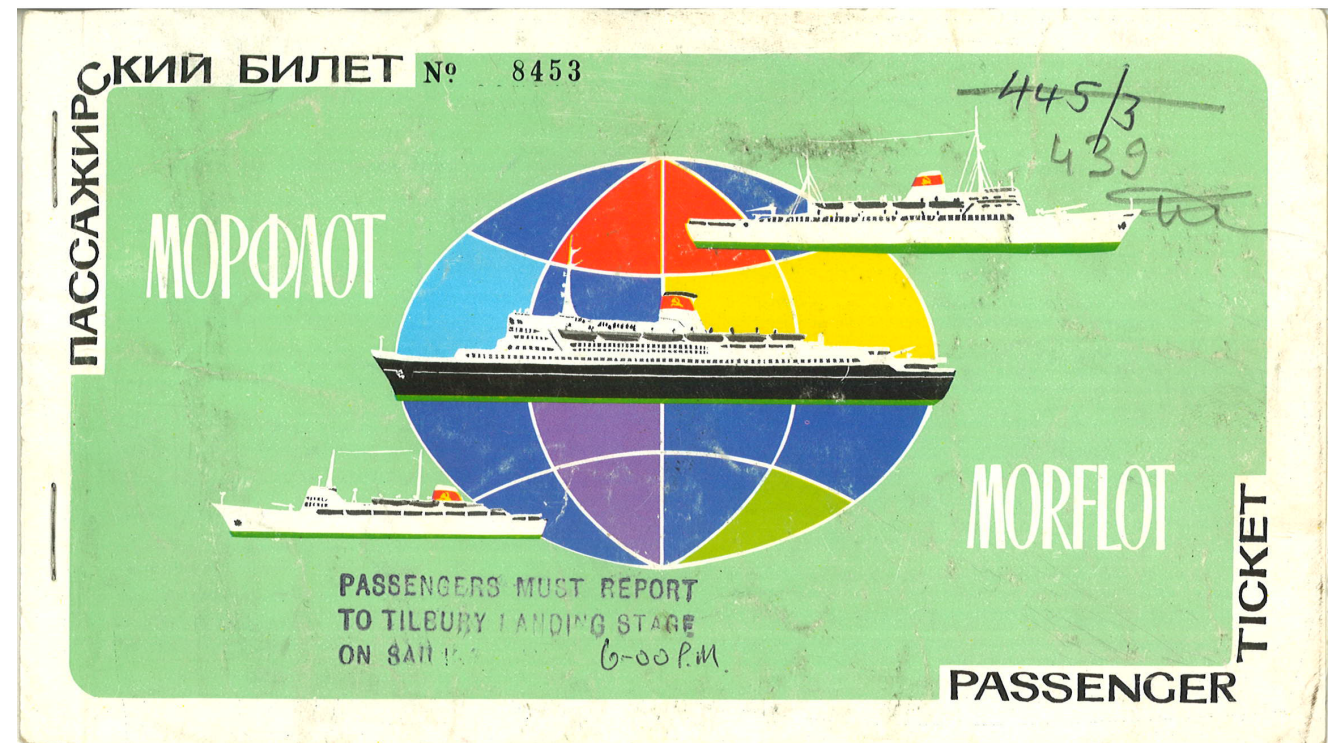


2015



# Historical remarks

- First visit to the US in 1977 on “Motorship Alexander Pushkin” — Fare ~\$200.
- Post-doc at MIT, (Radiative corrections to the DY process, K-factor)
- Post-doc at Caltech (ERT calculation allowing measurement of  $\alpha_s$  in  $e^+e^-$ ).
- Return to Europe in 1980.



БАЛТИЙСКОЕ МОРСКОЕ ПАРОХОДСТВО BALTIC SHIPPING COMPANY		
Билет Ticket	№ 08453	Класс Class
STUDENT		
Инициалы и фамилия Initials & surname	Возраст (для детей) Age of children	Тариф Rates
MR. R. ELLIS		1140-00
Скидки — Rebates		%
За проезд — Fare		
Сборы Taxes		посадка embarkation
		высадка disembarkation
Всего получено Total received		1140-00
Наименование и сумма полученной валюты Kind & sum of currency paid		4-00
		1-45
		1145-05
От — From LONDON		
До — To MONTREAL		
Каюта № Cabin No.	445	Место № Berth No.
		3
Судно — Ship ALEXANDER PUSHKIN		
Дата отхода Sailing date 12TH JUNE 1977		
Печать и подпись агента Stamp & signature of Agent		
1/3, Lower Regent St., London SW1Y 4NN		
25 MAY 1977		
(место и дата выдачи — place & date of issue)		
LONDON - 25th MAY 1977		



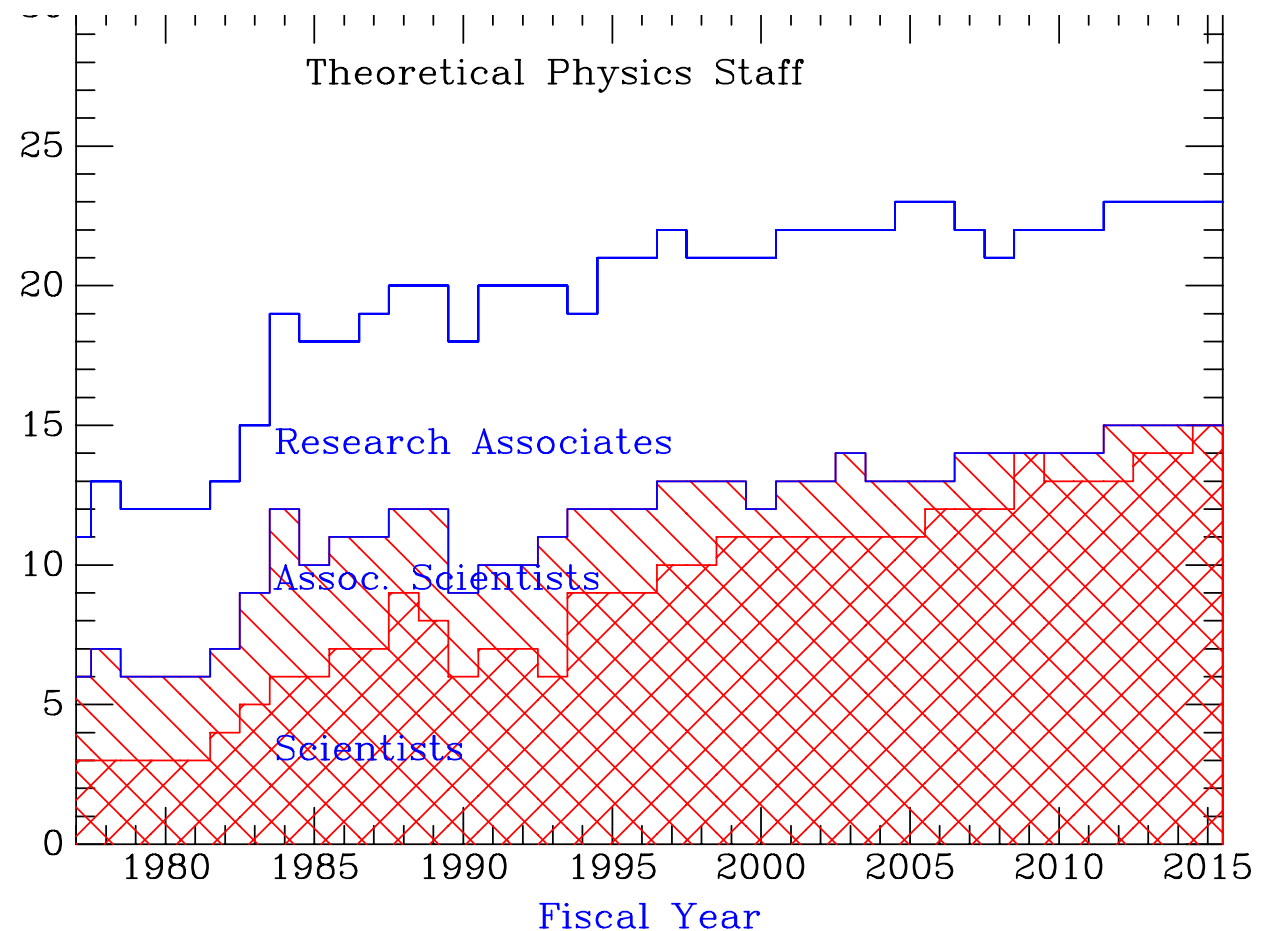
# Return to USA

- Abandoned a semi-permanent position in Rome to come to Fermilab
- Took up Associate Scientist appointment at Fermilab, on April 1st, 1984.

Cognome <u>ELLIS</u> (Nom - Name - Naam)	Foto del titolare della carta Photo du titulaire Lichtbild des Inhabers Foto van houder
Nome <u>Richard Keith</u> (Prénoms - Vorname - Voornamen)	FIRMA DEL TITOLARE Signature du titulaire Unterschrift des Inhabers Handtekening van houder
Cognome da nubile <u>///////</u> (Nom de célibataire - Mädchenname - Meisjesnaam)	
Data di nascita <u>17.11.1949</u> (Date de naissance - Geburtsdatum - Geboortedatum)	
Luogo di nascita <u>Aberdeen</u> (Lieu de naissance - Geburtsort - Geboorteplaats)	
Cittadinanza <u>inglese</u> (Nationalité - Staatsangehörigkeit - Nationaliteit)	
Residente a <u>Roma</u> (Résident à - Wohnort - Woonplaats)	
Via <u>Delle Terme di Tito, 92</u> (Rue - Strasse - Adres)	
Professione <u>ricercatore</u> (Profession - Beruf - Beroep)	
FIGLI MINORI DEGLI ANNI 16 (Enfants d'âge non supérieur à 16 ans - Angehörige unter 16 Jahren - Kinde- ren onder 16 jaar)	
Timbro dell'Autorità di P.S.	
Timbro	
	TIMBRO DELL'AUTORITÀ DI P.S. SALA 8 SOGGIORNO
	PROROGA DI VALIDITÀ Prorogation de validité Gültigkeitsverlängerung Verlenging van geldigheidsduur
	Prorogata sino al ..... (Prorogé jusqu'au - Verlängert bis - Verlengd tot)
	Firma e timbro dell'Autorità di P.S.
	Timbro
	Data ..... (Date - Datum - Datum)

# Theory Group

- In 1992 I was appointed by John Peoples as the head of the theory department.
- I served as head of the theory group from 1992 (when Bill Bardeen left for the SSC) until 2004, (with a sabbatical from 1995-1996).
- I had to handle all the standard stuff, travel, appointment of post-docs, promotions, reviews of the theory group (at that time, mercifully few and largely inconsequential).



# Safety Stand-down

- In 1998 we had to deal with the “Safety Standdown”
- Safety is clearly an important issue.
- As group leader I had to conduct the safety standdown.
- It was a struggle to identify real hazards in theoretical physics department....

SAFETY STAND-DOWN

- OUR RECORD IS NOT PERFECT
- ACTIVITIES FOR THIS PM.
  - WRITTEN JOB HAZARD ANALYSIS. (NOT NORMALLY REQUIRED.)

SUGGESTED TOPICS

- (a) GOING TO GIVE A SEMINAR IN EAST LANSING.
- (b) INSTALLING A COMPUTER WORK STATION.
- (c) ?

NAME, ~~DATE~~, SIGNATURE, ID #

- FUTURE JOBS FOR WHICH A WRITTEN HAZARD ANALYSIS IS REQUIRED.  
NAME, SIGNATURE, ID #

COMMENTS ON THE PROPOSED HAZARD GUIDELINES.

- ANY CURRENT CONDITIONS WHICH PEOPLE CONSIDER UNSAFE
- RETURN TO OFFICES
- TIME UNTIL 3-30pm TO BE DEDICATED TO HOUSEKEEPING, OFFICE CLEANLINESS.

STEPLADDER  
ELECTRICAL  
OUTLETS.  
NO CHAIRING  
SURGE PROTECTION

SIGN ON WATER FOUNTAINS.

REQUEST NEW CHAIRS

FRONT STEPS ILLUMINATION.

December 16, 1998

Theoretical Physics and Astrophysics Groups

Future Jobs for which written Job Hazard Analysis Required.

It is our considered opinion that as of today none of the jobs in the Theoretical Physics and Theoretical Astrophysics Departments in the foreseeable future present sufficient risk to require a written Job Hazard Analysis. All signatories are aware that they are free to revoke this decision and bring potentially risky tasks to the attention of their supervisor should circumstances change in the future.

Name	Id#	Signature
WILLIAM A. BARDEEN	2579	Will A. Bardeen
Estia J. Eichten	5332	Estia J. Eichten
Chris Quigg	1826	Chris Quigg
WALTER T GIELE	8899	W. Giele
James N. Simone	10651	James N. Simone
EWAN D. STEWART	11858	Ewan D. Stewart
SCOTT DODELSON	9950	Scott Dodelson
EDWARD KOLB	6056	Edward Kolb
Stephen Parke	6129	Stephen Parke
Joseph Lykken	8759	Joseph Lykken
Andreas Kronfeld	8170	Andreas Kronfeld
John Campbell	12276	John Campbell
Zoltan Ligeti	12313	Zoltan Ligeti
KEISUKE J. JUGE	12283	Keisuke J. Juge
Albin Stenlund	7478 <sup>1</sup>	Albin Stenlund
Hsin-Chia Cheng	11570	Hsin-Chia Cheng
Ulrich Nierste	12312	Ulrich Nierste
Konstantin Matchev	11881	Konstantin Matchev
PAUL MACKENZIE	5317	Paul Mackenzie PTO

Keith Ellis

# 6364

KEITH ELLIS

Keith Ellis, W&C, 8/21/2015



## Algebraic manipulation & Schoonschip



Schoonschip was Veltman's algebraic manipulation program, which I ran as a plugin to the Atari-1040



## Transitions

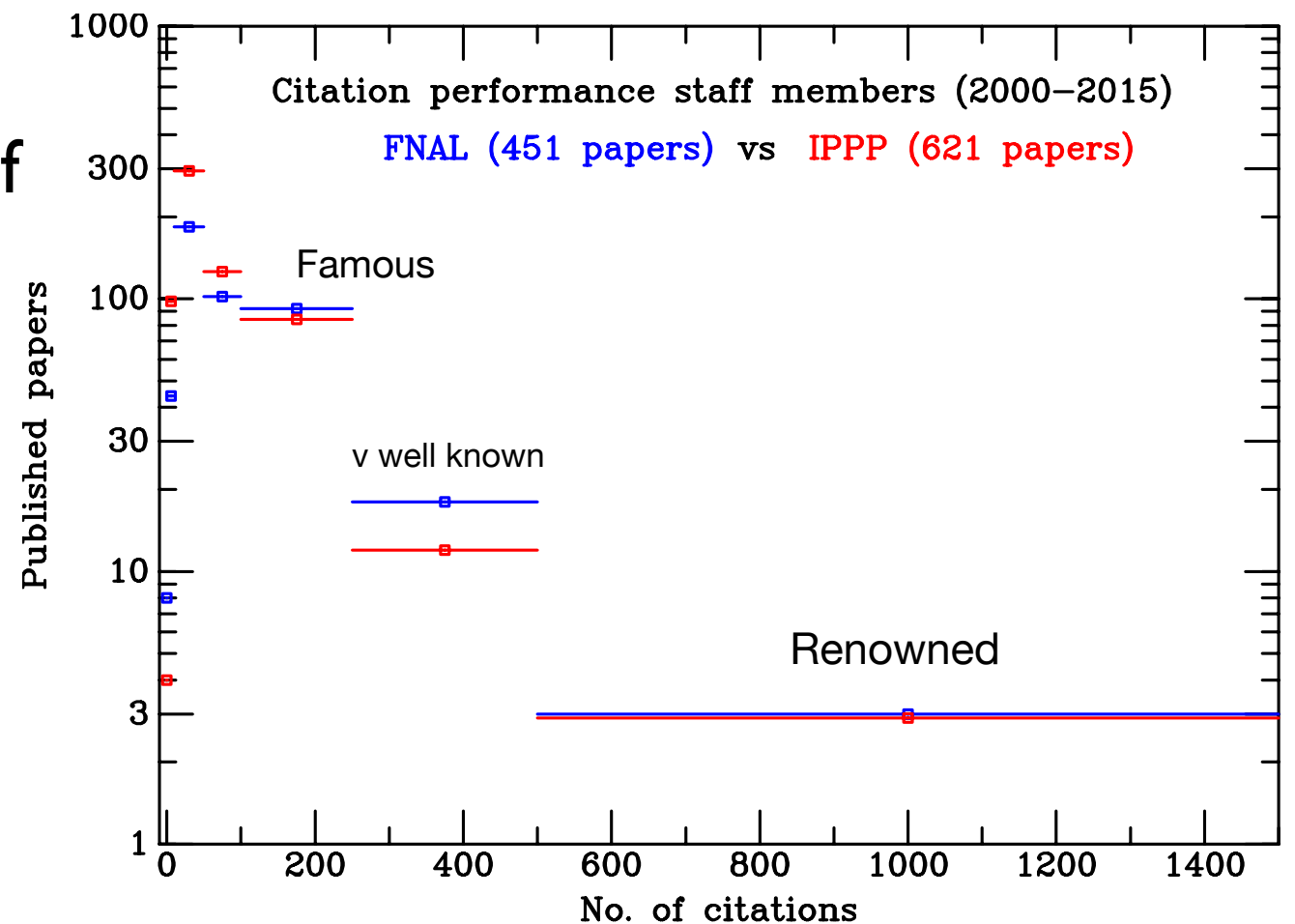
- Director of Institute of Particle Physics Phenomenology (IPPP) in Durham from 10/1/2015
- Durham is a university and cathedral city, (a wee bit south of the Scottish border).
- 10/1/2015  $\longrightarrow$  1/10/2015
- color  $\longrightarrow$  colour
- renormalization  $\longrightarrow$  renormalisation?
- 8 1/2" x 11"  $\longrightarrow$  A4  
(shorter and broader  $\longrightarrow$  narrower and longer?)





# IPPP: research record

- Some measure of the standing of the group can be obtained by the citation record, cf. the Fermilab theory group.
- Conclusion — the two groups are roughly commensurate.
- I hope to continue a close working relationship with Fermilab.
- I hope that my colleagues in the theory department will continue to hire Durham students.



DURHAM UNIVERSITY  
**STRATEGY**  
2010 – 2020  
Excellence in Research and Education

**Aim 2: To develop high-quality international partnerships, networks and collaborations in all our areas of activity.**

Thank you